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Fire-LCA Model: Cables Case Study

Brandforsk Project 703-991

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Abstract

A novel Life-Cycle Assessment (LCA) model has been defined for the investigation of the environmental impact of the choice of material in cable production. In one case polyolefin based material is used while in the other case PVC material is used. In both cases equivalent fire behaviour is assumed and a fire model is established based on existing fire statistics. This study represents the second full application of the Fire-LCA model.

Large-scale cable experiments have been conducted to provide fire emission data as input to the LCA model. Species measured include acute toxicants such as: CO, CO₂, HCl, VOC (volatile organic compounds), and chronic toxicants such as PAH (polycyclic aromatic compounds), and chlorinated dibenzodioxins and furans.

Four different End-of-Life scenarios have been selected for detailed study. The effect of the choice of cable life time and the level of secondary fires (i.e. cable fires where the cables are not the first item ignited) are also investigated. A comparison is made between models with a cable life time of 30 years and one with a cable life time of 50 years. Similarly, the level of secondary fires is varied between the worst case, based on an assumption that all large dwelling fires result in destruction of all the cable material in the house in the fire, and 10 % of this scenario.

Detailed results are presented for the energy use for the model and the emission of a number of key species to the air are presented for all scenarios. The results are presented to best allow comparison between the various scenarios for the same product but do also allow comparison between the products within each scenario.

An uncertainty analysis has also been performed to ensure that the conclusions are not prone to large uncertainty. The results of this analysis show that the model is stable and the species presented in detail are not affected to any great degree by changes in key parameters. This implies that the model is robust and the conclusions sound.

KEY WORDS: Flame retardant, fire, LCA, material recycling, landfill, energy recovery

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Sammanfattning

Kablars miljöpåverkan beroende på val av isoleringsmaterial har undersökts med hjälp av en modifierad LCA analys, den så kallade Fire LCA-modellen. Fire LCA modellen inkluderar även emissioner från bränder till skillnad från konventionella LCA modeller. Bränderna kan vara primära dvs. branden startar i kabeln eller sekundära, då startar branden någon annanstans. Tillgänglig brandskade statistik utnyttjas som indata till modellen.

I studien jämförs en PVC kabel med en kabel med ett polyolefin baserat isoleringsmaterial. Kablarna har likvärdiga prestanda och därför valdes en kilometer kabel som funktionell enhet. De båda kablarna antas dessutom ha likvärdigt brandbeteende.

Emissioner i form av CO, CO₂, HCl, VOC (lättflyktiga organiska ämnen), PAH (polycykliska aromatiska kolväten), klorerade dibenzodioxiner och furaner mättes vid två olika fullskaleförsök för varje kabel, ett välventilerat och ett underventilerat försök.

Analysen gjordes för fyra olika "End-of-Life" scenario;

- 100 % koppar och plast till deponi,
- 100 % plast till deponi, 100 % materialåtervinning koppar
- 100 % energiåtervinning plast, 100 % materialåtervinning koppar

Hur valet av livslängd på kabeln påverkar resultatet undersöktes. Livslängden har valts till dels 30 år dels 50 år. Vidare undersöktes inverkan av hur mycket kablar man antar måste ersättas till följd av de sekundära bränderna, det antogs att 100 respektive 10 % av kablarna i en bostad måste ersättas efter en brand. Detta visade att framförallt emissionerna av TCDD-ekvivalent (dioxiner och furaner), oförbrända kolväten och SO₂ påverkades av hur mycket kablar som måste ersättas efter en sekundär brand.

Eftersom kablarna hade likvärdigt brandbeteende i denna studien till skillnad från tidigare studier där man har jämfört flamskyddade och icke flamskyddade komponenter studerades även inverkan på resultatet av inkluderandet av bränder. Detta gav att emissionerna av framförallt TCDD-ekvivalent, HCl, CO och oförbrända kolväten påverkades av inkluderandet av bränder i LCA analysen.

I rapporten presenteras resultatet av analysen i form av energianvändning och emissioner presenteras för de olika scenarierna i en form för att underlätta jämförelse mellan de olika kablarna och mellan olika scenarier.

Slutligen gjordes en osäkerhetsanalys av resultaten som visade att modellen är robust.

Executive Summary

A novel Life-Cycle Assessment (LCA) model has been defined for the investigation of the environmental impact of the choice of material in cable production. In one case polyolefin based material is used while in the other case PVC material is used. In both cases equivalent fire behaviour is assumed and a fire model is established based on existing fire statistics. This study represents the second full application of the Fire-LCA model.

Large-scale cable experiments have been conducted to provide fire emission data as input to the LCA model. Species measured include acute toxicants such as: CO, CO₂, HCl, VOC (volatile organic compounds), and chronic toxicants such as PAH (polycyclic aromatic compounds), and chlorinated dibenzodioxins and furans. These results are the most detailed measurements of their kind for fully developed cable fires and provide a realistic input to the LCA model. Further, the effect of vitiation on the production of fire gases has been investigated.

Four different End-of-Life scenarios have been selected for detailed study. These are:

- 100% landfill plastics and copper
- 100% landfill plastics, 100% material recycling copper
- 100% energy recovery plastics, 100% material recycling copper
- 100% material recycling plastics, 100% material recycling copper

These scenarios have been selected to focus on extreme situations. In real life one would expect a percentage of material to go to recycling in some form that would be less than 100 % but more than 0 %.

Detailed results are presented for the energy use for the model and the emission of a number of key species to the air are presented for all scenarios. The results are presented to best allow comparison between the various scenarios for the same product but do also allow comparison between the products within each scenario.

The effect of the choice of cable life time and the level of secondary fires (i.e. cable fires where the cables are not the first item ignited) are also investigated. A comparison is made between models with a cable life time of 30 years and one with a cable life time of 50 years. The results of this analysis show that while the impact per year is less if one assumes a longer life time for the cable the total impact is higher.

Similarly, the level of secondary fires is varied between the worst case, based on an assumption that all large dwelling fires result in destruction of all the cable material in the house in the fire, and 10 % of this scenario. This assumption results in an assumption that between 0.4 % and 4 % of the 1 million km of cables used as the functional unit should be replaced due to secondary fires. The results of this analysis show that the level of the secondary fires only has a major effect on the emission of TCDD-equivalents, unburned hydrocarbon, and SO₂.

An uncertainty analysis has also been performed to ensure that the conclusions are not prone to large uncertainty. The results of this analysis show that the model is stable and the species presented in detail are not affected to any great degree by changes in key parameters. This implies that the model is robust and the conclusions sound.

KEY WORDS: Flame retardant, fire, LCA, material recycling, landfill, energy recovery

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List of Abbreviations

BaP	benzo(a)pyrene
Fire-LCA	LCA model modified to include fires
FR	flame retardant
FTIR	fourier transformation infrared spectrometry
HpXDD/F	heptahalogenated dibenzodioxin/furan (halogen = chlorine or bromine)
HRR	heat release rate
HxXDD/F	hexahalogenated dibenzodioxin/furan (halogen = chlorine or bromine)
ISO	International Standardisation Organisation
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LOQ	limit of quantification
MLR	mass loss rate
N.A.	no analysis made of this species
N.D.	not detected, i.e., below the LOQ
NFR	non-flame retardant
OXDD/F	octahalogenated dibenzodioxin/furan (halogen = chlorine or bromine)
PAH	polycyclic aromatic hydrocarbons
PnXDD/F	pentahalogenated dibenzodioxin/furan (halogen = chlorine or bromine)
ppm	parts per million
SEMKO	Swedish National Electrical Safety Board
SETAC	Society of Environmental Toxicology and Chemistry
SPR	smoke production rate
T _{ig}	ignition temperature
t _{ig}	ignition time
TOC	total organic carbon
TXDD/F	tetrahalogenated dibenzodioxin/furan (halogen = chlorine or bromine)
UL	Underwriters Laboratories
VOC	volatile organic compounds

1 Introduction

Fires have always been a part of our society both in term of controlled fires, or combustion, for heating purposes and uncontrolled accidental fires. Accidental fires cause a substantial amount of damage both economically and in terms of human lives. Society spends large amounts of money each year on fire prevention and the financial results of fires are well documented. The environmental impact of fires, however, has only recently come under scrutiny^{1,2}.

A conventional environmental study is usually focused on one aspect of the environmental impact of some human behaviour. However, human activities are usually complex and involve and influence many different parts of our society. It is, therefore, important to find a method to analyse an entire product or process to achieve a more general analysis of our activities. The Life-Cycle Assessment (LCA) concept is presently the most common method to analyse an entire process system in terms of energy, resources and environmental aspects. The method offers a well-defined procedure and has been chosen as a platform for this study.

Recently² a novel LCA model, the so called Fire-LCA model, was presented and applied to a consumer electronic appliance (TV) where the environmental effect of fires was incorporated into the overall treatment of the environmental impact of the product. This application provided insight into the environmental impact material and design choices made in the manufacture of the TV aimed at increasing the fire safety of the product. Two versions of a 27 inch TV were compared. In the first case the TV complied with the European requirements as outlined in IEC 60065 while in the second case the TV complied with the US requirements as outlined in UL1410. Minor differences in the requirements in these standards have prompted industry to adopt the use of outer housing material with differing fire performance in Europe and the US. Any picture of the environmental impact of material choices is naturally complex. Significantly for the Fire-LCA model, however, one found that the different scenarios that were studied gave rise to large differences in overall emissions. Thus, this first application illustrated well the usefulness of this approach.

This model has now been extended for application to cables. In this report the new “Cables Fire-LCA” model is presented and an application is discussed. Aspects such as end-of-life scenarios, fire statistics, and fire scenarios and large scale fire performance of cables is discussed together with the straw LCA model defined for cables.

The choice of cables as the second application of this new model has been based on a number of important activities that have been ongoing concerning cable fire performance in recent years. Research into the testing and classification of cable fire performance has been investigated in two major international research programs^{3,4}. Results from these projects have indicated that the fire performance of cables is important for the fire development in a given building fire scenario and that large volumes of cables are present in buildings worldwide. Based on the fact that the majority of cables worldwide (again with the exception of the US) have fire performance defined by IEC 60332-1 large volumes of these cables are present in modern buildings. This performance implies that the cables are able to be ignited and will burn under certain conditions.

The first application of the Fire-LCA model compared two products with different fire performance. In contrast, this second application compares two cables with similar fire performance constructed from different materials. This scenario or comparison was deemed more relevant due to the fact that the majority of installation cables exhibit the

fire performance chosen in this study while the question of material choice is continually debated.

The choice of cables for the specific application used to illustrate the model in this study was governed by the current dominant material choice and a so called “Green Line” alternative. The current dominant material choice is PVC while the alternative is a polyolefin based polymer that has been combustion modified to exhibit similar fire performance to the PVC cable. Throughout the report, these cables will be referred to as the “PVC cable” and the “CASICO cable”.

A description of the Fire-LCA model as applied to cables is presented in the next chapter while the fire model used to define the flow of material and products into the Fire part of the LCA model is discussed in Chapter 3. This fire model is based on discussions with industry and available international fire statistics. The model is in itself uncertain due to uncertainties in the input to the various fire statistics data bases. An effort has been made to mitigate this source of error by taking averages of statistical data from several sources. Details of the model, the method used and assumptions made in its construction are summarised in Chapter 3 to facilitate assessment of the validity of the choices made. The results of the LCA calculations are also presented both with and without the fire aspects of the model included to provide a measurement of the importance of this part of the model in the overall emissions.

A large number of fire experiments have been conducted to provide input to the LCA model concerning emissions from fires. The results of these experiments are summarised in Chapter 4 and Appendices 1 and 2. A full discussion of the importance of the small scale investigation in defining the conditions for the large scale experiments is included in this material.

The results for a large number of applications of the LCA model to both the PVC and Green Line cables are presented in Chapter 6 and conclusions in Chapter 7. The results are presented for 4 different scenarios to establish the importance of end-of-life alternatives. Further, the impact of the choice of cable lifetime and fire model are investigated and presented.

The results indicate that while the picture of emissions is complex the impact of inclusion of fire emissions into an overall determination of the environmental impact of material choice in cables manufacture is valid. The lifetime of the cable is not a determining factor in the relative environmental impact of the four different scenarios. In other words, extending the lifetime of the cable from 30 to 50 years does not alter the relative size of the various emissions.

1.1 References

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2 LCA Model

Life-Cycle Assessment (LCA) is a versatile tool to investigate the environmental aspects of a product, a process or an activity by identifying and quantifying energy and material flows for the system. The use of a product or a process involves much more than just the production of the product or use of the process. Every single industrial activity is actually a complex network of activities that involves many different parts of the society. Therefore, the need for a system perspective rather than a single object perspective has become vital in modern research. It is no longer enough to consider just a single step in the production. The entire system has to be considered. The Life-Cycle Assessment methodology has been developed in order to handle this system approach. A Life-Cycle Assessment covers the entire life-cycle from the “cradle to grave” including crude material extraction, manufacturing, transport and distribution, product use, service and maintenance, product recycling, material recycling and final waste handling such as incineration or landfill. With LCA methodology, it is possible to study complex systems where interactions between different parts of the system exist.

LCAs are also a much better tool to evaluate the environmental impact of a chemical substance used in a product than purely hazard based assessments. Hazard based assessments look only at the potential for environmental damage by focusing on the hazardous characteristics of a substance and worst case use scenarios without taking account of how the substance is actually used, and of possible environmental benefits or costs resulting indirectly from the function of the substance

The prime objectives are:

- to provide as complete a picture as possible of the interactions of an activity with the environment;
- to contribute to the understanding of the overall and interdependent nature of the environmental consequences of human activities; and,
- to provide decision-makers with information that defines the environmental effects of these activities and identifies opportunities for environmental improvements.

Applications for an LCA can be many and some are listed below, divided into internal and external use for an organisation:

Internal

Knowledge generation

Strategic planning

Development of prognoses

Development of environmental strategies

Environmental improvement of the system

Design, development and optimisation of products or processes

Identifying critical processes for the system

Development of specifications, regulations or purchase routines

Environmental audit

Waste management

External

Environmental information

Environmental labelling

Environmental audit of companies

An LCA usually evaluates the environmental situation based on ecological effects and resource use. In a few cases, the work environment has also been included. An ordinary LCA does not cover the economic or social effects. In an LCA, a model of the real system is designed. This model is of course a representation of the real system with various approximations and assumptions.

The life-cycle approach is in fact not new. It existed in the 1960's although early models only considered energy flows. In the late 1980's a more general environmental approach was formed. The methodology was further developed in the early 1990's based on ideas from Europe and the USA. Basic ideas concerning the methodology were originally defined in the SETAC (Society of Environmental Toxicology and Chemistry) document "Guidelines for Life-Cycle Assessment: A Code of Practice" from 1993¹. Since then, different documents have been published in different countries but the basic theories are relatively similar. In the Nordic countries for example the "Nordic Guidelines on Life-Cycle Assessment" (1995) has been published as a guideline, not a standard⁶.

The International Organization has prepared international standards for LCA methodology for Standardization (ISO). The following standards are available today.

- Principles and framework (ISO 14040)²
- Goal and scope definition and inventory analysis (ISO 14041)³
- Life cycle impact assessment (ISO 14042)⁴
- Life cycle impact interpretation (ISO 14043)⁵

Generally the method can be divided into three basic steps with the methodology for the first two steps relatively well established while the third step (Impact assessment) is more difficult and controversial. The first two steps are usually referred to as the life cycle inventory (LCI) and can be applied separately without the following impact assessment. In addition to the different steps in the procedure there can also be an interpretation phase. The three basic steps are shown in Figure 1 below.

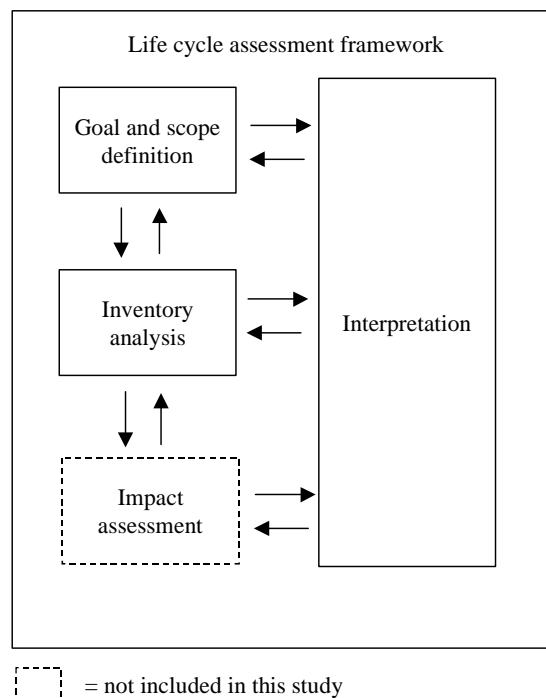


Figure 1 Basic steps in an LCA.

The *Goal Definition and Scoping* consists of defining the study purpose, its scope, project frame with system boundaries, establishing the functional unit, and establishing a strategy for data collection and quality assurance of the study. Any product or service needs to be represented as a system in the inventory analysis methodology. A system is defined as a collection of materially and energetically connected operations (e.g., manufacturing process, transport process, or fuel extraction process) that perform some defined function. The system is separated from its surroundings by a *system boundary*. The whole region outside the boundary is known as the *system environment*.

The *Functional Unit* is the measure of performance that the system delivers. The functional unit describes the main function(s) of the system(s) and is thus a relevant and well-defined measure of the system. The functional unit has to be clearly defined, measurable, and relevant to input and output data. Examples of functional units are "unit surface area covered by paint for a defined period of time", "the packaging used to deliver a given volume of beverage", or "the amount of detergents necessary for a standard household wash." It is important that the functional unit contains measures for the efficiency of the product, durability or life time of the product and the performance quality standard of the product. In comparative studies, it is essential that the systems be compared on the basis of equivalent function.

Other important aspects to consider in the goal definition and scoping include:

- Whether the LCA is complete or if some component is excluded from the study.
- Which type of environmental impact is considered in the study?
- A description of important assumptions.

In the *Inventory Analysis* the material and energy flows are quantified. The system within the system boundaries consists of several processes or activities e.g. crude material extraction, transports, production, and waste handling. The different processes in the system are then quantified in terms of energy use, resource use, emissions etc. The processes are then linked together to form the system to analyse. Each sub-process has its own functional unit and several in- and outflows. The final result of the model is the sum of all in- and outflows calculated per functional unit for the entire system.

In an inventory analysis, products can move across system boundaries. In these situations it is necessary to distribute (allocate) the environmental impact to the different products. In principle, 3 types of allocations can be distinguished.

- *Multi-output*: Several products are produced in the same factory e.g. crude oil refinery.
- *Multi-input*: Different products into a single unit e.g. waste incineration
- *Open-loop recycling*: In recycling processes where the material is used outside the system boundaries.

Several allocation principles exist such as:

- *Physical* or *chemical* allocation based on natural causality.
- *Economical* or *social* allocation.
- Allocation based on an *arbitrary choice of a physical parameter* such as mass, volume, energy content, area or molar content.

The most difficult part and also the most controversial part of an LCA is the *Impact Assessment*. No single standard procedure exists for the implementation of impact assessment although generally different methods are applied and the results compared. Due to the complexity of the model used here, a qualitative assessment has been done for a number of significant species. This is presented in Chapter 5.

In the *valuation* phase, the different impact classes are weighed against each other. This can be done qualitatively or quantitatively. Several evaluation methods have been developed. The methods that have gained most widespread acceptance are based on either expert/verbal systems or more quantitatively methods based on valuation factors calculated for different types of emissions and resources such as Ecoscarcity, Effect category method (long and short term), EPS- system, Tellus, Critical volume or Mole fraction. Due to the fact that many important emission species from fires (in this particular study: dibenzodioxins and furans, and PAH, PCB etc.) are either not dealt with in detail or not available at all, these methods are not suitable for an objective interpretation of environmental impact. Thus, a qualitative comparison method has been found to be most beneficial.

In some cases, the LCA analysis is followed by an *interpretation phase* where the results are analysed. This phase provides an opportunity for the discussion of the results in terms of safety aspects. The fact that people may die in fires and that flame retarded products cause a reduction in the number of fire deaths cannot be included explicitly in the LCA. This should be, and is, discussed together with the results of the LCA analysis to provide a context for their interpretation and a connection to the reality of fire safety.

An LCA study has theoretical and technical limitations. Therefore, the following parts of a system are usually excluded:

Infrastructure: Production of production plants, buildings, roads etc.

Accidental spills: Effects from abnormal severe accidents. In the new “Fire-LCA” model, fires are included but not industrial accidents during production.

Environmental impacts caused by personnel: Waste from lunch rooms, travels from residence to workplace, personal transportation media, health care etc.

Human resources: Work provided by humans is not included.

An LCA analysis usually covers energy use, use of natural resources and the environmental effects. In an entire decision making process the LCA results and the environmental aspects are only a part of all the decision factors such as economic factors, technical performance and quality, and market aspects such as design.

2.1 The risk assessment approach

In a *conventional* Life-Cycle Assessment, the risk factors for accidental spills are excluded. For example, in the LCA data for the production of a chemical, only factors during normal operation are considered. However, there can also be, for example, emissions during a catastrophic event such as an accident in the factory. Those emissions are very difficult to estimate due to a lack of statistical data and lack of emission data during accidents. The same type of discussion exists for electric power production in nuclear power plants.

In the case of the evaluation of normal household fires, the fire process can be treated as a commonly occurring activity in the society. The frequency of fire occurrences is relatively high (i.e. high enough for statistical treatment) and statistics can be found in most developed countries. This is expanded in Chapter 3. This implies that it is possible to calculate the different environmental effects of a fire if emission factors are available.

Previously, the Fire-LCA model has been used to evaluate the effect of choosing different levels of fire safety in a given product⁷. The higher level of fire safety in the previous work was attained using flame retardants. The introduction of flame retardants into the products changed the occurrence of fires and the fire behaviour. By evaluating the fire statistics available, with and without the use of flame retardants, the environmental effects could be calculated. The benefits of the flame retardant were thereby weighed against the “price” society has to pay for their production and handling.

This present application will be a modification of the original Fire-LCA model in that we will concentrate on two products with essentially equivalent fire behaviour and investigate what effect the choice of material in the products has on the environmental impact if we take into account the risk for involvement in a fire.

2.2 Project methodology

The Life-Cycle Assessment methodology that will be used in this project is based on normal LCA methodology in combination with different fire experiments. This methodology is described in the ISO standard 14040-series and other documents from different countries in Europe and the USA. The standards used in this study are ISO 14040 and ISO 14041.

2.3 Computer modelling methods

Different computer software solutions for LCA calculations exist. Generally, the software can be divided into two different groups:

- Specific Life-Cycle Assessment programs, (KCL-ECO, LCA Inventory Tool, SimaPro etc.).
- General calculation programs such as different spread sheet programs (Excel etc.).

In addition to the different LCA calculation programs, several database structures for storage of LCA data and meta-data exist.

For this project a specific LCA tool, KCL-ECO has been selected. KCL-ECO is a versatile tool for performing LCA studies. With KCL-ECO you can easily build LCA system models and calculate results for the system. It is also easy to aggregate modules into new modules and create new systems based on existing modules. The program can handle processes as well as transports and material flows between modules. KCL-ECO is basically a program for solving linear equations. It is therefore easy to handle material recycling processes. However, non-linear processes cannot be calculated in the program. These can be calculated separately in other programs and inserted into KCL-ECO as constants. It is also possible to include sensitivity analysis, classification and different valuation methods based on valuation factors such as Ecoscarcity, the Effect Category Method and the EPS-system.

2.4 The Fire-LCA system description

Schematically the LCA model used for the analyses of fire behaviour can be illustrated as in Figure 2. The model is essentially equivalent to a traditional LCA approach with the inclusion of emissions from fires being the only real modification. In this model, a func-

throughout. In those cases where alternatives exist these will be considered as ‘best’ and ‘worst’ cases or as ‘present’, ‘possible future’ and ‘state-of-the-art’ technologies. These alternatives can be presented as possible scenarios and the effect of the choices made can be illuminated by comparisons between the various scenarios.

System Boundaries: According to standard practice, no account will be taken of the production of infrastructure as defined earlier in this chapter or impact due to personnel. Concerning the features of the model that are specifically related to fires the system boundaries should be set such that they do not appear contrived. In general, it is realistic that we assume that material that is consumed in a fire would be replaced. Where possible we will rely on literature data to ascertain the size of such contributions. In lieu of such data, an estimate of the contribution will be made based on experience of similar systems. In the case of small home fires, which are extinguished by the occupant without professional help, the mode of extinguishment will not be included due to the difficulty in determining the extinguishing agent. In cases where the fire brigade is called to a fire, transport and deployment will be included as realistically as possible. In the present application of this model this has, however, not been included.

Emissions from fires: A wide variety of species are produced when organic material is combusted. The range of species and their distribution is affected by the degree of control in the combustion process. Due to its low combustion efficiency a fire causes the production of much more unburned hydrocarbons than does a controlled combustion. In the case of controlled combustion, one would expect that carbon dioxide (CO₂) emissions would dominate. In a fire, however, a wide variety of temperature and fuel conditions and oxygen availability are present. Thus, a broader range of chemical species, such as CO, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC, HC(air)), particles, and dibenzodioxins and furans must be considered.

The above choices provide the framework for the Fire-LCA. They should not be seen as insurmountable boundaries but as guidelines. As intimated above, in most applications of an LCA it is common to propose a variety of scenarios and to investigate the effect of the choices involved. Typically the system boundaries may be defined in different ways and the effect of this definition can be important for our understanding of the model.

2.5 Cable Case Study

In the present research study two, different types of electrical cables have been evaluated in terms of resource, energy and environmental behaviour. The two cables represent two different materials that can be used in the production of electrically comparable cables. Generally, cables differ in conducting and isolation materials. The classic conductor materials for cables have been copper but aluminium is also used frequently today. Since the polymeric materials have been available, they have been used frequently for isolation and cover of cables. Of the polymers, PVC has been the most common plastic for cables. However, due to the environmental issues connected with PVC, alternative materials for cables have been developed and are today used frequently. The new cables are halogen free and usually based on polyethylene.

In this study, two different cables have been evaluated. One traditional PVC cable and one cables based on polyethylene (a CASICO cable). Both cables have copper conductors. The cables represent ordinary power cables used in households. The cables have been selected to be relatively equal in function and in fire behaviour. A more detailed cable specification can be found in Appendix 4.

The question is how the environmental behaviour is for the two different cables and especially in relation to the fire behaviour. To be able to cover a broad aspect of the environmental behaviour a system perspective has been used in the analysis. The Fire-LCA concept has been applied and LCA models for the two different cable alternatives have been designed. The structure of the models is shown in Figure 3 and Figure 4.

Each module in the model is described in the inventory presentation of this report. An overview of the system is given in this chapter.

Generally, the model can be divided in three parts.

- Cable production (including material production).
- Waste handling (including landfill, incineration and recycling).
- Fires related activities (including fires and material replacement).

The life-cycle of a cable starts with the production of the different raw materials used in the cable production. In this case production of copper and production of different plastic materials are used. Plastic materials are a mixture of different materials designed for a specific quality. In cable production, plastic materials can be bought with a specific quality or plastics can be mixed at the cable production site. The materials used in the model are described in each module from “cradle to factory gate”.

The function of the cables used in this study is to transport electric power. It is however difficult to use electric power as the functional unit for model. Usually, the power capacity of the cable is much higher than the actual average power load during the lifetime. The actual power load is unknown and can vary significantly. It can thus be misleading to relate the data to a certain power level. The two cables used in the study have been selected to have an equal power capacity. In this case, it is possible to use a specific quantity of cable as the functional unit for the model. Thus, as the *functional unit* of the model 1 million km of cables produced have been chosen. This unit represents a very large quantity of cables. The unit is aimed to be used on a country based scale.

From the cable production, the cables are delivered to the users of the cable. No electrical power loss has been assumed for the cable during its lifetime. Thus, no environmental burden has been put on the use of the cable. The cables are then used during their entire lifetime. The average lifetime of a household cable has been estimated to 30 years. After the regular lifetime, the cables are handled in the waste handling modules. Three different waste handling possibilities are used in the model.

1. Waste (cables) to landfill.
2. Waste (cables) to incineration.
3. Waste (cables) to material recycling.

In the waste handling procedure the proportion of the different waste handling alternatives are specified. The waste handling procedure can vary significantly over time and between different countries. Energy can be gained from the waste handling in two ways. The incinerated plastics generate energy and methane formed from landfilled plastics can be used to produce energy. The so formed energy has been calculated in the model and the formed energy has been assumed to replace fuel oil heating. In the models “External Steam/heat user”, “Oil boiler steam gain” and “Precombustion Oil, Oil boiler gain” the gained energy and emissions are calculated.

In the case of mechanical material recycling, the cables are first disassembled. The different materials are then transported to a specific material recycling process for each material. In this case, a copper recycling process and a process for recycling of thermoplastics. From the disassembly process the material that are not recycling, can be trans-

ported to incineration or landfill. Copper from incineration ash can also be used for copper recycling. The processes do not include feed stock recycling.

A minor part of the cables is involved in different fires during their lifetime. The end of life for these cables are thus different from ordinary cables both in respect to time and end of life process. The Fire-LCA concept has been used to handle the fire part of the model. With the use of fire statistics, a number of different cable fires have been identified. The fires can involve not only the cables but also an entire room or house. From the fire statistics, the number of fires per year and per million km of cables in use has been identified and this information has been used in the model to calculate the amount of cables that are involved in the different types of fires and the extent of the fires. A fire will shorten the life time of the different products involved in the fire and those products must thus be replaced. An average of 50 % life time reduction has been assumed in the model. Thus, only 50 % of the material is replaced. Modules for the production of the replaced materials or products are also included in the model.

Transports are included in the model and are shown as a “dash” on the flow arrows between the different modules. Truck transport has been assumed for all the transport activities. Electric power is supplied to the different modules from the electric power production modules. An OECD electric power production mix has been assumed in the model. The model has three different power units that are used to distinguish between power production for different parts of the model.

The types of parameters that are important in the various models are summarised in Table 1. Other parameters may be included as required.

Table 1 Examples of the types of input and output parameters that are important in the various modules.

Input parameter	Output parameter
Energy	Energy
(Electric power)	Recovered heat
Coal	Materials/products
Crude oil	Produced products
Natural gas	Emission to air
Hydro power	CO ₂ -fossil
Nuclear power	CO ₂ -biogenic
Natural resources	CO
Crude oil	NO _x
Metals (Fe, Al, Zn, Au, Pt etc.)	SO _x
Other minerals	HC, VOC etc.
Natural products (wood, cotton etc.)	HCl
Etc.	H ₂ S
	Chlorinated organic compounds
	Particles
	Metals (Hg, Cd, Pb, etc.)
	Emissions to water
	COD
	BOD
	HCl
	Chlorinated organic compounds
	Organic compounds
	N-total
	P-total
	Particles, suspension
	Metals (Hg, Cd, Pb, etc.)
	Solid material and waste
	Volume, area occupation etc.
	Organic contents
	Metals (Hg, Cd, Pb, etc.)
	Chlorinated organic compounds
	Organic compounds

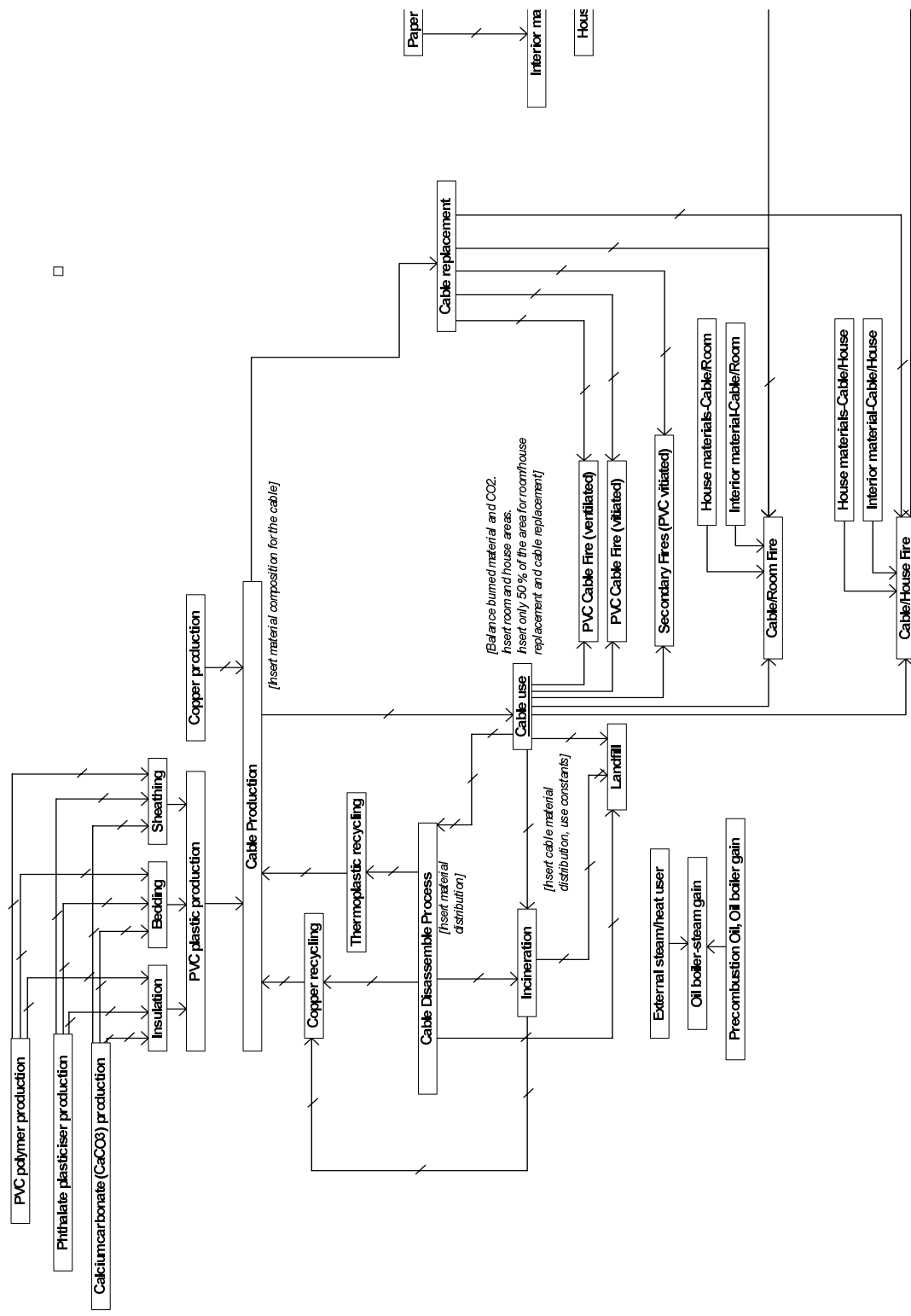


Figure 3 LCA model structure for the PVC cable.

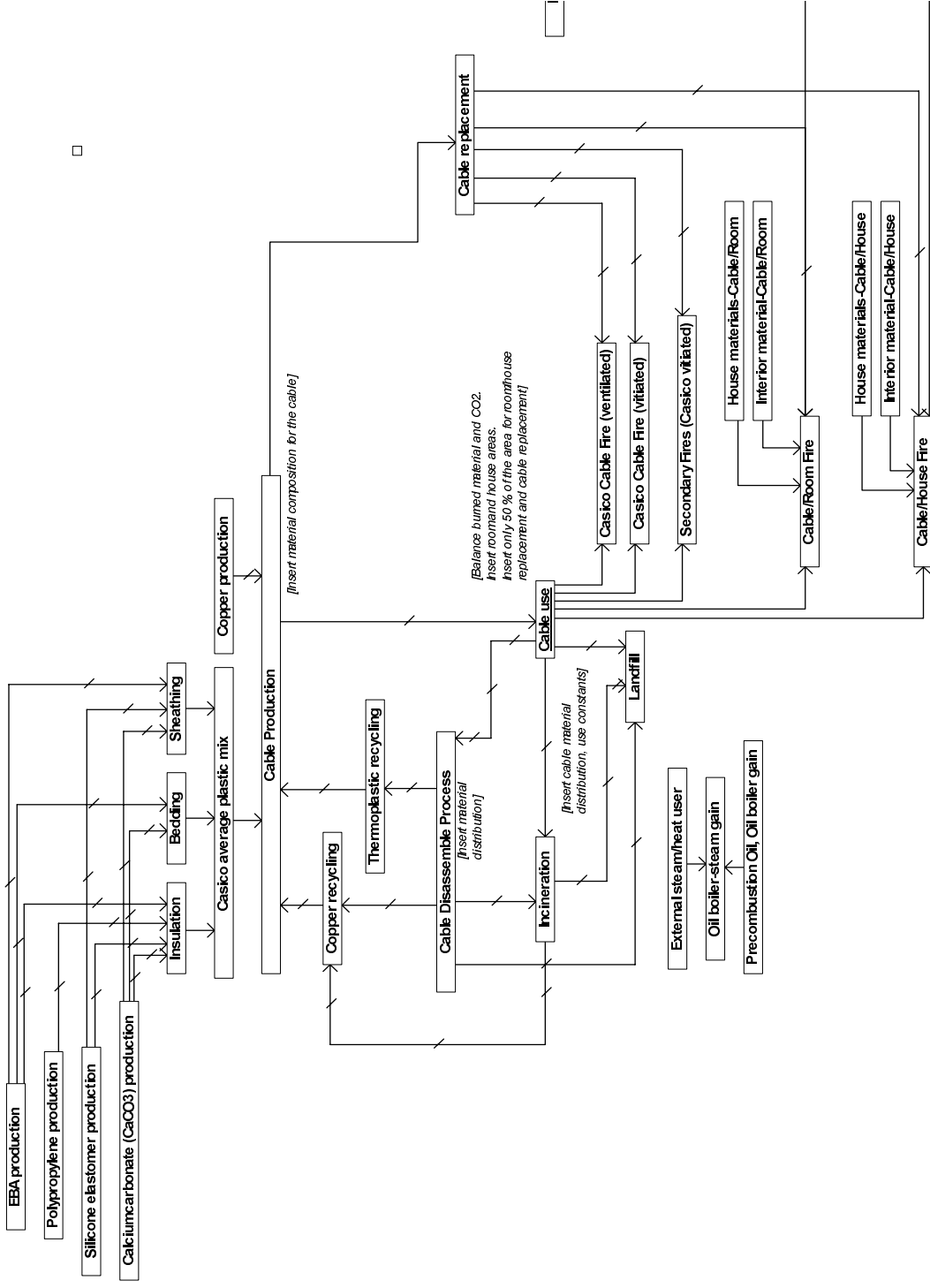


Figure 4 LCA model structure for the CASICO cable.

2.6 References

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3 Fire Model

A large body of fire statistics is available world-wide concerning fires in cables. The available statistics vary depending on the source, and information from different sources has been combined to create the full model. To incorporate the environmental impact of fires in the LCA models, statistics describing the occurrence of fires *caused* by electrical cables, so called *primary fires*, have been used. Also, fires that are *not caused* by electrical cables, but where the cable material burns as a part of the fire, so called *secondary fires*, are included. The statistics regarding the amount of cable material destroyed in both primary and secondary fires also has to be included in the LCA models. Details of the primary and secondary fire models are summarised below.

3.1 Primary fire model

Primary fires are defined as those where the cable is the first item ignited. The size of this type of fire may vary, from a fire where the cable is the only item ignited, to a serious fire destroying large amounts of property. In the LCA model described in Chapter 2 the primary fire categories are defined by the modules labelled: “Cables Fire”, “Cable/Room Fire”, and “Cable/House Fire”. Secondary fires are defined as all fires where cables are involved but where cables are not the first item ignited, i.e. the cable is not the object causing the fire. Using available European statistics (with a focus on UK and Swedish statistics due to their availability and detail) an approximate fire model has been defined for use in the Cables Fire-LCA model.

Using fire statistics collected from countries in Europe¹⁻⁸, it has been estimated that a total amount of 35 fires occur per million dwellings due to cables. Based on data from Denmark⁹, each dwelling is estimated to contain (on average) 250 m of cable, and it is assumed that approximately 50 m of cables are present on average in a single room. This corresponds to 140 fires per million km of cables that can be assumed to be caused by electrical wiring and cables, i.e. so called primary fires.

Using statistics mainly from the UK Home Office and from SRV Sweden³⁻⁷ concerning distribution of the size of the fire (the fire spread), the number of fires that are confined to the cable only (“Cables Fire”), spread beyond the cable but contained in the room of origin (“Cable/Room” fires) and those that cause significant damage to the dwelling (“Cable/House” fires) can be estimated. The results of this division are summarised in Table 2.

Using the result of these calculations together with information regarding the total amount of cables in a typical dwelling it is possible to estimate the length of cables burned in primary fires each year, and thus the amounts of cables burned in 30 years, which is the estimated lifetime of the cables used in the LCA model¹⁰⁻¹¹. The final result of these calculations are values (in percent), which describes the amount of cables, which are destroyed in primary fires, of the total amount of cables used in the LCA model. These values are used as input in the model, see Figure 5.

Table 2 Calculation procedure of fire statistics.

	Fire spread (%)	Fires (nr.)	Cable length burned/year (m)	Cable length burned in 30 years (km)	% of 10^6 km cables
Cables fire	60	84	2100	63	0,0063
Cable/Room fire	31	43	2150	64,5	0,00645
Cable/House fire	9	13	3250	97,5	0,00975

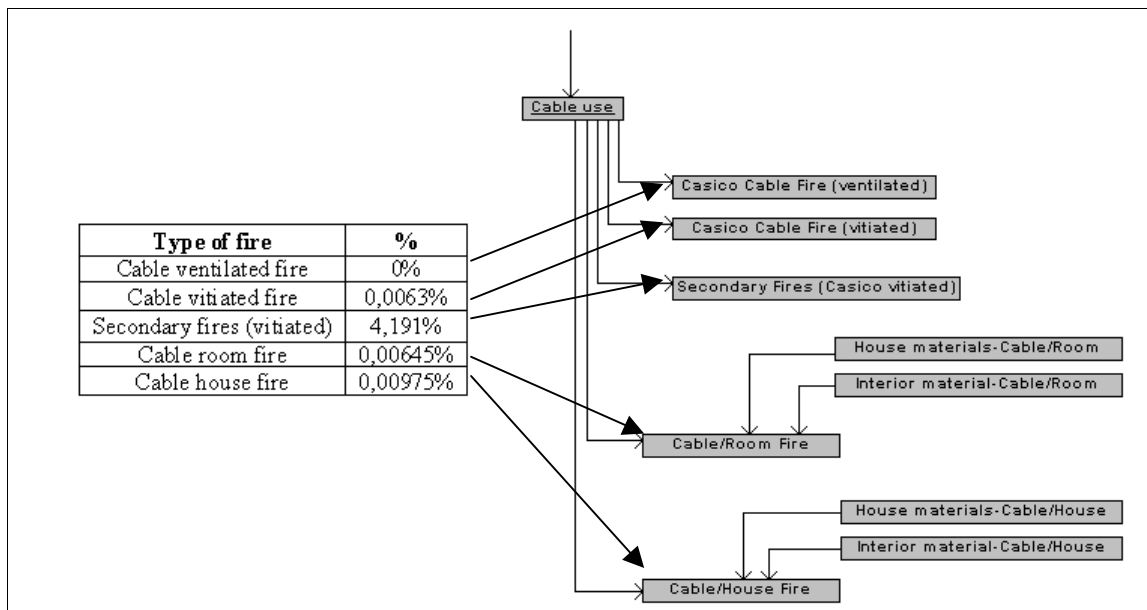


Figure 5 The incorporation of fire statistics in the LCA model.

Further, it is assumed that 50 % of all the cables in the room in the “Cables only” category are involved in the fire.

It is estimated that all “Cable fires” are vitiated, i.e. emissions data for this module are based on the results from the vitiated cable experiments. When a cable fire starts, the atmosphere in the vicinity of the fire may be well ventilated, but as the fire develops and progresses, the atmosphere becomes vitiated. Due to this behaviour, all fires used in the LCA model are estimated to be vitiated fires, but as a complement a module describing well ventilated “Cable fires” is included in the model. An investigation of the impact of using the results of the “well ventilated” experimental data into this module instead of the vitiated data indicates that the impact is small using the experimental emissions we had available. The next chapter contains a discussion of the experimental results, which explains this in more detail.

As seen in Table 2, the amounts of cables destroyed in primary fires, as a part of the total amount of cables used in the model, are very small. This is a reflection of the fact that very little statistical evidence is available that fires begin in cables and electrical wiring.

During the search of statistics, no information could be found about how important the choice of cable material (e.g. PVC or PE) is regarding the frequency of electrical fires. No information could be found where the amounts of fires caused by cables were, or could be, distributed based on the specific material used in the cables causing the electric fires. Thus, it has been assumed that there is no difference between the fire models that are used in the two cable LCA models.

3.2 Secondary fire model

Based again on UK Home Office statistics and statistics from SRV Sweden it has been estimated that approximately 1400 serious fires occur annually per million dwellings¹². Serious fires are fires where the dwelling is severely damaged, or totally destroyed, by the fire. It is assumed that there is approximately 250 m cable per dwelling. By using this number and the estimated amount of serious fires occurring annually per million dwellings, the corresponding amount of serious fires per million km of cables is 5600.

The total length of cables that is destroyed each year in serious fires is 1400 km, if it is assumed that 100% of the cables present in the dwellings are destroyed. This amount of cables is used in the model as a “worst case scenario”, where all cables in the dwellings are assumed to be destroyed. If the estimated life time of the cables is 30 years, 42000 km of cables is destroyed in serious fires during the life cycle of the cable, or 4,2% of the total amount of cables that is used in the LCA model!

As part of this study we have also investigated the sensitivity of the results to the number of secondary fires by including a scenario where we assume that only 10% (instead of 100%) of the amount of cables used in the dwellings that are exposed to serious fires are actually destroyed in the fire. If 10% of all the cables in each dwelling are destroyed, this corresponds to 140 km of cables that are destroyed in fires each year. This has been used as a “realistic estimate” of the contribution of secondary fires and is compared to the worst case scenario in the results chapter.

3.3 References

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4 Fire Experiments

4.1 Introduction

When developing the methodology for the large-scale experiments, very useful information can be obtained by performing small-scale fire experiments. It was deemed that an investigation of the fire gases produced by the cables under a variety of degrees of ventilation and temperature was appropriate to determine the possible species that may be produced in the large scale experiments. To facilitate this a number of small scale DIN 53436 tube furnace were performed with varying degrees of ventilation.

The types of cables studied in this project are often installed in ventilation shafts and ducts, where the air availability in a fire scenario mostly is low. In this vitiated atmosphere, the oxidation of the cable material being combusted in a fire scenario is not fully developed, thus producing less carbon dioxide and higher concentrations of various hydrocarbons and carbon monoxide, compared to the production in an atmosphere with normal oxygen concentration. Producing a vitiated atmosphere in the large scale experiments is, however, difficult given the basic set-up. Thus, the small-scale experiments performed in a vitiated atmosphere are of special interest although they do not provide direct input to the LCA.

In this chapter, the small scale experiments are described first with some interpretation of the implications of the small scale results on the large-scale tests. The aim of the small-scale experiments was to study the performance of the cables under various conditions that can appear in the beginning of, or during, a fire scenario. The design of the experiments and the experimental equipment are discussed in the subsequent sections of this chapter.

4.2 Choice of cables

Installation cables were chosen for this Cables Fire-LCA Case Study. This choice was governed by a number of different factors including volume (in terms of sales), availability, applicability to data available in fire statistics.

In this modification of the Fire-LCA model as described in Chapter 2 two products with equivalent fire behaviour are studied. The cables both pass the IEC 332-1 test and cannot be described as high fire performance (or plenum) cables. They represent, rather, traditional indoor installation applications. A cable with PVC mantle over PVC insulation and one with a polyolefin mantle over polyolefin insulation have been selected in this study. A photo of each is shown in Appendix 1.

Specific details concerning the cable dimensions and input to the Cable Production module of the Fire-LCA model are summarised in Appendix 4.

4.3 Small-scale experiments

4.3.1 Test apparatus

The test apparatus used was a *DIN 53436 tube furnace*. This furnace was connected to an FTIR instrument: *BOMEM MB 100* equipped with a *DTGS* detector. The gas cell in the FTIR was an *Infrared Analysis M-38H-NK AU*. The program used for the analysis was *GRAMS/386 v 3.01b* (*Galactic Industries Corporation*). A *J.U.M Engineering Heated Total Hydrocarbon analyser model VE5* flame ionisation detector (FID), was connected in series with the FTIR instrument. No external pump was connected to the system, as the FID was equipped with a pump.

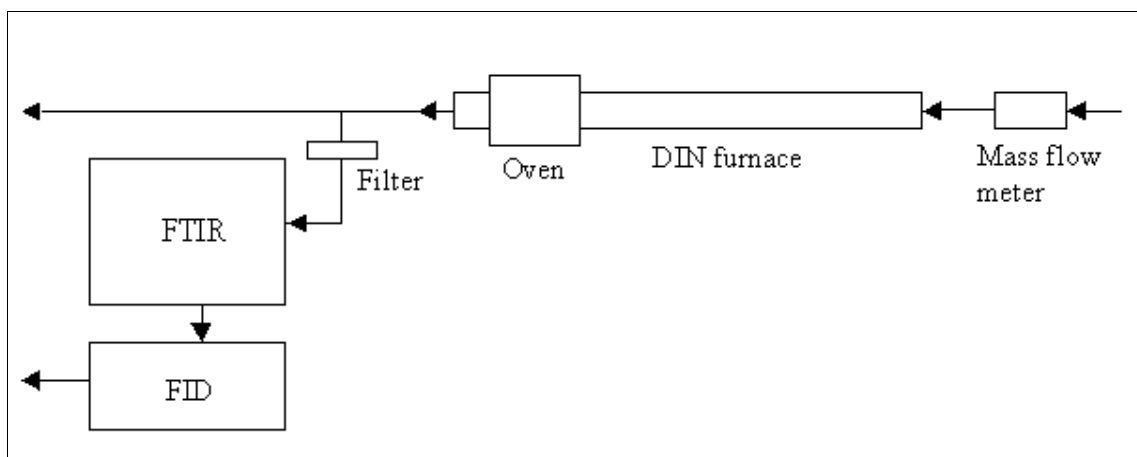


Figure 6 Schematic representation of experimental apparatus.

A mass digital flow meter was connected to the system before the air entered the DIN 53436 furnace¹. A filter was attached, between the DIN furnace and the FTIR, to remove particles from the gas flow from the furnace. This filter was heated to eliminate condensation of water from the fire gases before they were transported to the FTIR for analysis. A schematic representation of the experimental apparatus is shown in Figure 6.

This furnace consists of a quartz tube, about 1 meter long, onto which a furnace, approximately 20 cm long, is attached. The furnace can be heated to a desired temperature and starts to move along the quartz tube with a constant velocity of 10 mm/min. The material, placed on a sample boat inside the tube, is continuously ignited, producing combustion gases at a relatively constant rate.

The oxidant flows through the quartz tube from one end, at an optional flow, in the opposite direction to the movement of the furnace, thus avoiding preheating of the material by the hot decomposition products produced during the experiment. The gas stream carrying the combustion products is transported directly to analysis.

4.3.2 Test method

To study the cable materials of interest, two temperatures (350 °C and 650 °C) and two oxygen concentrations (5% and 21%) were chosen. 350 °C was chosen since pyrolysis processes usually have started at this temperature, producing fuel for the combustion process. A temperature of 650 °C is usually sufficient to ignite the pyrolysis gases being produced, starting a fire that can be maintained and that may develop. Thus, by choosing these temperatures, two of the most important stages of the fire scenario could be studied.

Based on ISO 9122:1 and experience of using the DIN oven in other experiments (TOXFIRE and HCN)^{2,3} it was determined that well ventilated combustion could be accomplished if an air flow rate relative to sample loading of 100 mg sample/l air was used. The vitiated conditions were accomplished by using a loading of 400 mg sample/l air.

The sample was chosen to consist of approximately 1/3 of a cable length, including one of the isolated wires. The length of the sample was 30 cm. The weight of the combustible material in each sample was 8,4 g. During the experiments where the 100 mg sample/l air ratio was used, synthetic air was used. When performing the experiments with the 400 mg sample/l air, a gas flow with 5% of oxygen (synthetic air diluted with nitrogen gas) was used, instead of increasing the weight of the sample.

The airflow during the experiments was 2.8 l/min, of which 1.7 l/min were transported to the analysis equipment. The product gases were transported from the DIN furnace to the FTIR, and from the FTIR to the FID, in a heated sampling tube maintained at 150 °C. The temperature in the gas cell in the FTIR was also maintained at 150 °C in accordance with recommendations for use of FTIR in fire experiments obtained from the SAFIR project⁴.

The sheath and insulation of the cable was placed on top of the wire before placing the sample in the furnace. By doing like this, the risk of flame propagation along the wire that could be faster than the flame propagation along the sheath and insulation material was reduced.

The FID was calibrated using propane gas. Thereafter, a nitrogen gas flow of 2 l/min was passed through the FTIR cell and the FID for some minutes, to ensure that the equipment did not contain any contaminants from previous experiments. The gas flow used in the system was controlled with the mass flow meter, and the filter was heated with a hot air gun to approximately 150 °C. The oven was started, and when the temperature specified for the experiment was reached, the pump in the FID was started, and the flow in the system was controlled before the analysis equipment was connected to the quartz tube. The sample was placed in the sample boat 5.0 cm from the end of the boat closest to the oven, and then inserted in the quartz tube. The boat was placed with its front edge in line with the edge of the furnace. The air flow was connected to the furnace, and the FTIR analysis program and the FID were started. The oven was started after the air flow had been on for 5 minutes. The experiment continued until the oven had fully passed the sample in the boat, and the fire had fully ceased.

4.3.3 Results and Conclusions

The DIN furnace experiments were designed to assist the planning of the large scale experiments and the results are not used directly as input to the Fire-LCA model. Thus, the results are not discussed in detail in this chapter but can be found in their entirety in Appendix 2. Instead the conclusions based on an analysis of the experimental results and their repercussions for the large scale tests are summarised in the next section.

When comparing the results from the well ventilated and the vitiated experiments, the largest difference could be seen when studying the results obtained from the experiments performed with the CASICO material. The ventilation dependence was largest for this material. The production of non-combusted hydrocarbons increased about ten times when the oxygen concentration was decreased at 650 °C. The production of non-combusted hydrocarbons from PVC increased only about 40% when the oxygen concentration was decreased at 650 °C.

The production of non-combusted hydrocarbons at 350 °C decreased when the oxygen concentration was decreased. The difference between the productions at the two ventilation ratios was again largest in the experiments with the CASICO material. The production from the CASICO material decreased with about 40%, and the production from PVC decreased with about 6%.

The temperature dependence was also largest for the CASICO material. When increasing the temperature from 350 °C to 650 °C at 100 mg sample/l air, the production of non-combusted hydrocarbons increased by about 120%, and when increasing the temperature at 400 mg sample/l air, the production increased by 4100%. In the case of the PVC material, the change in the production of unburned hydrocarbons was smaller. At 100 mg sample/l air, the increase was 24%, and 90% at 400 mg sample/l air.

The large difference between the temperature dependence of the two materials can be explained by comparing the fire performance of the two materials during the experiments at 350 °C. The weight decrease of the PVC material during the experiments at 650 °C resulted in a weight loss of approximately 5 g, and at 350 °C the weight loss was about 4 g. The CASICO material, however, had a large difference in the weight loss between the experiments at the two temperatures. The weight decrease during the experiments at 650 °C resulted in a weight loss of approximately 5 g, but the weight loss at 350 °C was only about 0.2 g (0.3 g at 100 mg sample/l air, and 0.1 g at 400 mg sample/l air). Thus, the large difference in the production of hydrocarbons from the CASICO material between the two temperatures can be explained by the fact that the weight loss from the CASICO material was very small at 350 °C, which resulted in a low production of hydrocarbons.

The production of low molecular weight compounds from the CASICO material was also highly temperature and ventilation dependent. The production of low molecular weight compounds from the PVC material differed between the two ventilation ratios and the two temperatures, but not as much as in the case of the CASICO material. The difference was most noticeable when comparing the experiments with the CASICO material performed at 650 °C. The concentration of CO₂ decreased 10 times when the oxygen concentration was decreased, while the concentration of CO increased approximately 8 times. When comparing the results obtained from the same tests on the PVC material, this difference is not as obvious. The decrease of the CO₂ concentration was only about 45%, and the production of CO did, in fact, also decrease. The cause of the decrease in

the production of CO is unknown, but may be explained by the increased production of non-combusted hydrocarbons.

It is apparent from the results described above that the degree of ventilation and temperature of the test has the greatest effect on the product distribution for the CASICO cables. This is probably due to the fact that under well-ventilated, high temperature conditions combustion of the CASICO material is very efficient. In contrast, the presence of large amounts of chlorine in the PVC material inhibits the combustion of the PVC cable even under well-ventilated, high temperature conditions. This implies that the combustion of PVC does not use even close to the stoichiometric amount of oxygen required for complete (or near complete) combustion of the organic material under well-ventilated conditions. When the amount of oxygen available is then seriously reduced in the vitiated experiments the oxygen required for combustion of the PVC material has not been greatly reduced. In other words we should expect that in the large scale experiments the combustion products from the PVC experiments would be similar independent of ventilation while those for CASICO will produce significantly larger amounts of unburned hydrocarbons in the vitiated experiments relative to the well-ventilated experiments.

Based on this knowledge of the expected behaviour of the combustion products it was determined that the well-ventilated CASICO experiment would be run first using a standard sampling method and if necessary the collection system would be increased to allow for the increased production of unburned hydrocarbons in the second vitiated experiment. The PVC experiments would be run last (well-ventilated and then vitiated) to minimise contamination of the sampling system with chlorinated species. As the sampling system was not clean (it has been used for numerous tests involving halogenated material) a blank sample was taken at the outset to ensure that correction of all species for background concentrations would be possible as part of the chemical analysis.

4.4 Large-scale fire experiments

Large scale experiments were performed according to a modified version of the IEC 332-3 standard. The combustion chamber was as specified in IEC 332-3. A schematic of the experimental set-up is shown in Figure 7. Gas analyses were performed in the exhaust duct placed above the chamber.

The chamber where the cables are mounted is often referred to as "the kiosk" since it looks like an old telephone kiosk. The kiosk is $1000 \times 2000 \times 4000 \text{ mm}^3$. It has a door opening large enough to facilitate easy mounting of the cable tray. There is an air inlet in the bottom of the kiosk, which is connected to a fan, which supplies an airflow of 6500 l/min. There is a glass window in the door to facilitate video recording and estimating flame spread during IEC 332-3 test. The ignition burner used was a 20 kW propane.

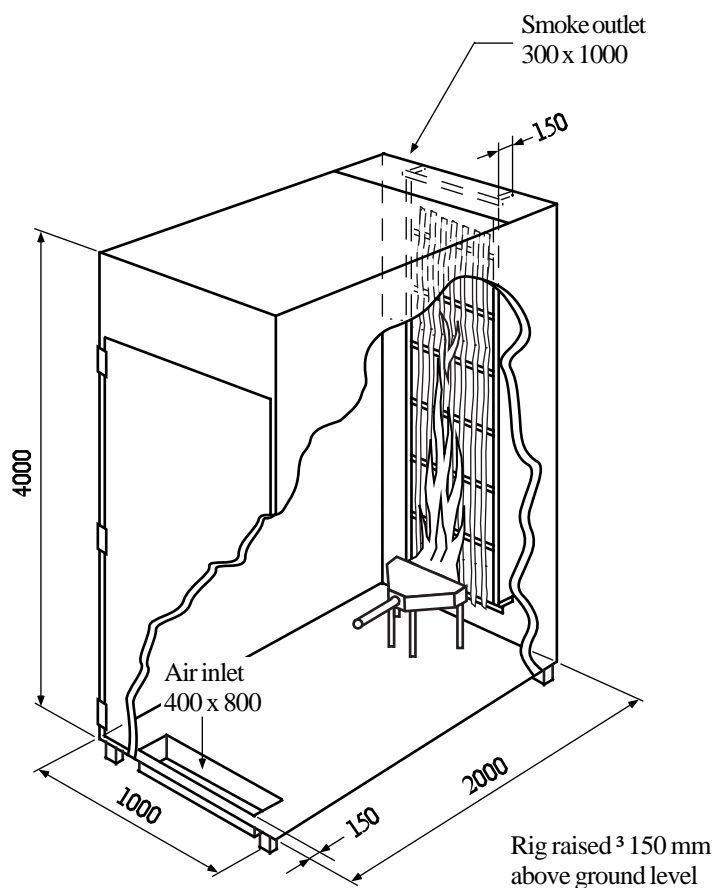


Figure 7 Schematic picture of IEC 332-3 set-up.

In addition, measurements were performed of the smoke gases in the exhaust duct above the kiosk. The Rate of Heat Release (HRR) was measured together with CO and CO₂ as in most fire tests. In addition FTIR measurements similar to those conducted in the small scale experiments were performed, together with chemical analysis of PAHs, dibenzodioxins, furans and Volatile Organic Compounds (VOC). The FTIR spectrometer is described in section 4.3 and the sampling and chemical analysis methodology in appendix 2.

The exhaust duct is 40 cm in diameter. The chemical analysis and FTIR measurements were made 2.5 m after any guide vanes or bends of the duct. The HRR, CO and CO₂ measurements were made 3.5 m after the guide vanes and bends. After each experiment the CO and CO₂ measurements performed with the FTIR and ordinary gas analyser were compared. The agreement was very good and only the FTIR results are presented in this report.

Two tests were performed for each cable, one well ventilated and one vitiated. In addition one blank test with a propane burner of 120 kW for 10 minutes was performed. In all cable tests, the weight of the cable tray before and after the test was registered to facilitate the calculation of yields). In addition material that had fallen onto the floor was collected and weighed. In all tests 15 cables 2.7 m long were mounted on the cable tray with one cable diameter between each cable.

In the well ventilated experiments, an airflow of 6500 l/min was supplied into the apparatus. However, the air available in the kiosk is substantial, and therefore in order to create a somewhat vitiated atmosphere in the vitiated experiments the airflow was switched off and a 100 kW burner was used for 2 and a half minute before igniting the cables. The extra burner consumed about $100 / 12.8 \times 2.5 \times 60$ g oxygen which means

that the oxygen concentration in the chamber when the cables was ignited was in excess of 10 %.

The quantification of the detected products has been conducted from the time when the burner, that ignited the cables, was started, until the end of the test. The burners used in the experiments are very efficient and produce mainly CO_2 from the combustion of carbon. The amount of CO_2 produced from the burners was subtracted from the amount of CO_2 detected by the FTIR. Thus, the amount of CO_2 presented in the tables represents the amounts of CO_2 produced by the decomposition process of the cables being studied.

It is estimated that the CO_2 produced by the first burner (used to lower the concentration of O_2) disappears quite fast in the ventilation duct. However, in the beginning of the quantification, there are still remains that might make the concentration of CO_2 a little bit too high (approximately 0,1%). A rough calculation indicates that the remaining CO_2 may enhance the total mass produced of CO_2 with about 1-2 %.

The amount of CO_2 produced by the burner is not subtracted in the figures describing the production of CO_2 . The small peak that can be seen in the beginning of the profile thus describes the formation of CO_2 from the first burner used for consuming the oxygen in the fire test rig.

4.4.1 Results – PVC experiments

The combustion gases that were detected and quantified during the analysis of the combustion product gases from the PVC cables were H_2O , CO_2 , CO and HCl . H_2O is not presented in the tables and figures that are presented in this report. Indications of the existence of other combustion products, such as ethylene, methane and acetylene, were found in the FTIR spectra. These, however, could not be quantified using this method.

Well-ventilated

The airflow in this experiment was approximately 6500 l/min. A total of 15 cables, each 2.70 m long were mounted on one side of the cable tray with one cable diameter between each. A pre-measurement time of 2 minutes was applied. The gas to the burner was switched off after 10 minutes 30 s. The cable tray before the test weighed 19.3 kg and after the test 17.5 kg. The material collected in the kiosk weighed 669 g, i.e. 1.1 kg material was burnt. About 18 cm were not burnt on the cables. This information was used in determining the input to the Fire-LCA model. The HRR for this experiment is shown in Figure 8.

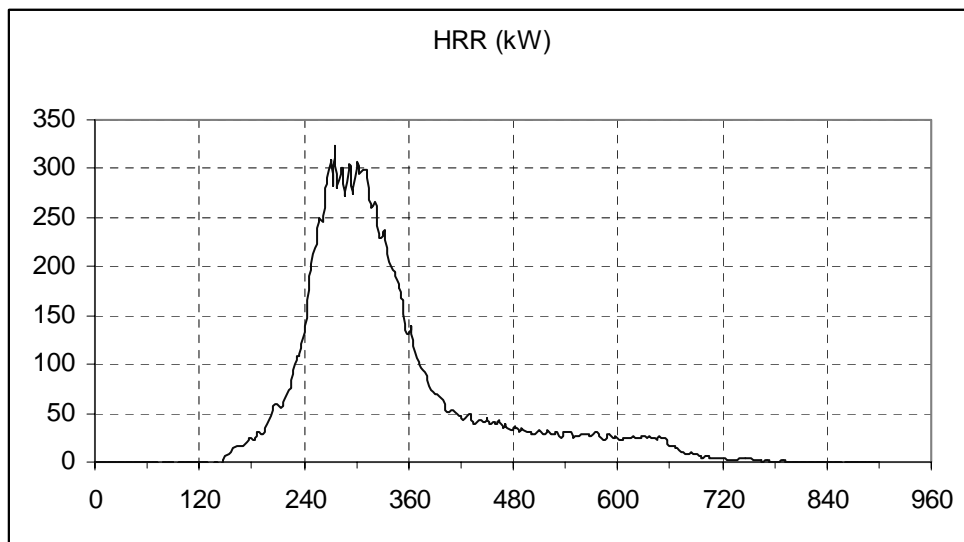


Figure 8 HRR for well-ventilated PVC test in IEC 332-3 rig.

A summary of the results from the analysis of this experiment can be seen in Table 3.

Table 3 Quantified product gases after subtraction of CO_2 produced by burner from the well-ventilated experiment with PVC.

		CO_2 (burner subtracted)	CO	HCl
Weight combusted material (g)	1100,0			
Length burned (m)	37,80			
Total mass produced (g)		2204,01	83,32	231,71
Yield (g/g)		2,0	0,08	0,21
Yield (g/m)		58,3	2,20	6,13
Max g/s		15,01	0,81	2,54
Max concentration.		1,2 %	1007,6 ppm	2421,0 ppm

Figure 9 shows the product profiles of the gases detected using FTIR during the experiment.

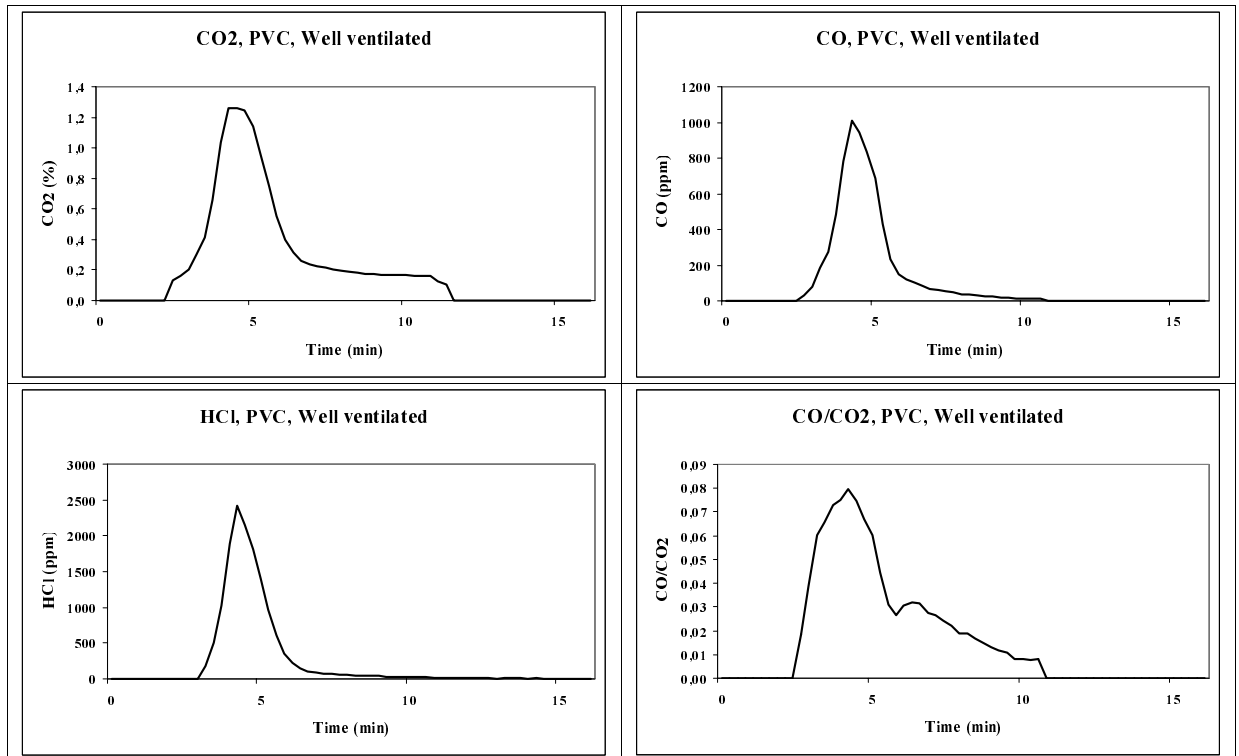


Figure 9 Product profiles of the gases detected using FTIR during the well ventilated experiment with PVC.

To examine how vitiated the atmosphere during the experiment was, the ratio between the CO and the CO₂ produced during the experiment can be investigated. The value of this ratio can indicate whether the atmosphere was well-ventilated or vitiated. If the ratio exceeds 1, it can be assumed that the atmosphere was vitiated, and if the ratio is below 1, the atmosphere can be considered well-ventilated. This is, however, not always true, as the amounts of CO and CO₂ being produced may also depend on which material is being studied. The ratio does, however, provide a good indication of relative vitiation. In the TV case study however the CO/CO₂ ratio was about 0.2 in the room experiments, which were considered to be vitiated.

As seen in Figure 9, the CO/CO₂ ratio reaches a maximum value at about 0.08 showing that the combustion process is well-ventilated.

Vitiated

No extra airflow was used in these experiments. An extra burner was ignited 3 minutes after start of measurement, the HRR of the burner was about 100 kW and the burner was on for 2 and a half minute. The burner used to ignite the cable was ignited 6 minutes after start of measurement. The burner was turned off 13 minutes after start of measurement. The tray before the test weighed 27.1 kg and 25.1 kg after. A total of 234 g material was collected at the floor, i.e. 1.8 kg material was burnt. About 12 cm were not burnt on the cables. The HRR for this experiment is shown in Figure 10.

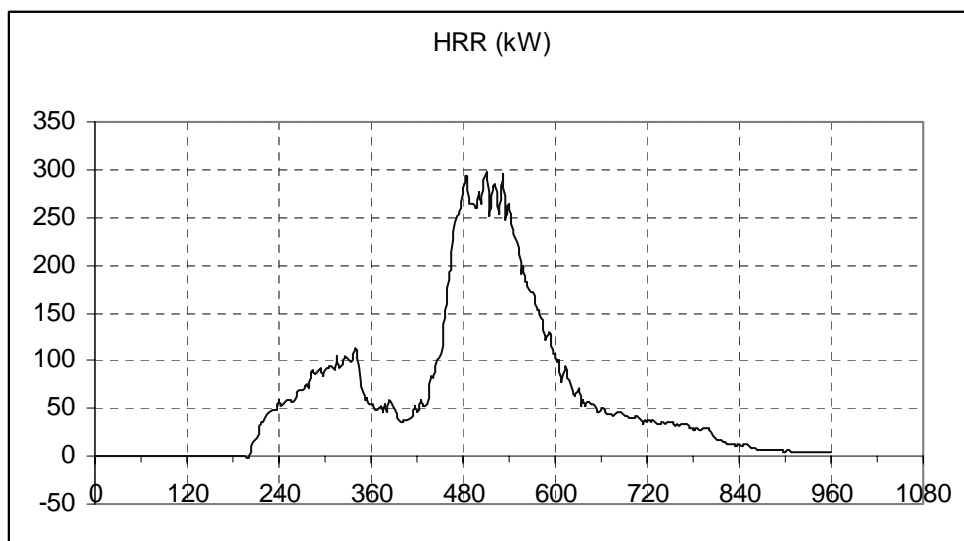


Figure 10 HRR for the "vitiated" PVC experiment in the IEC 332-3 rig.

A summary of the results from the analysis of this experiment can be seen in Table 4.

Table 4 Quantified product gases after subtraction of CO_2 produced by burner from the vitiated experiment with PVC.

		CO_2 (burner subtracted)	CO	HCl
Weight combusted material (g)	1800,0			
Length burned (m)	38,70			
Total mass produced (g)		2176,17	89,81	273,18
Yield (g/g)		1,21	0,05	0,15
Yield (g/m)		56,2	2,32	7,06
Max g/s		13,50	0,88	2,55
Max conc.		1,0 %	1087,6 ppm	2431,4 ppm

As seen in Figure 11, the CO/CO_2 ratio reaches a maximum value at about 0,10. The difference between the well-ventilated and the vitiated experiment is quite small, ~25% if the peak value is considered. Since the chlorine in the PVC inhibits the combustion, however, the difference between well-ventilated and vitiated conditions should not be especially large. This is due to the inhibiting mechanism of the chlorine, which reduces the amount of CO being converted into CO_2 . This leads to quite high concentrations of CO even under well-ventilated conditions, and therefore a rather small difference in the CO/CO_2 ratio between well-ventilated and "vitiated" conditions. Due to this, it is quite difficult to say how vitiated the conditions were during this experiment. This is in agreement with that expected from the small scale experiments.

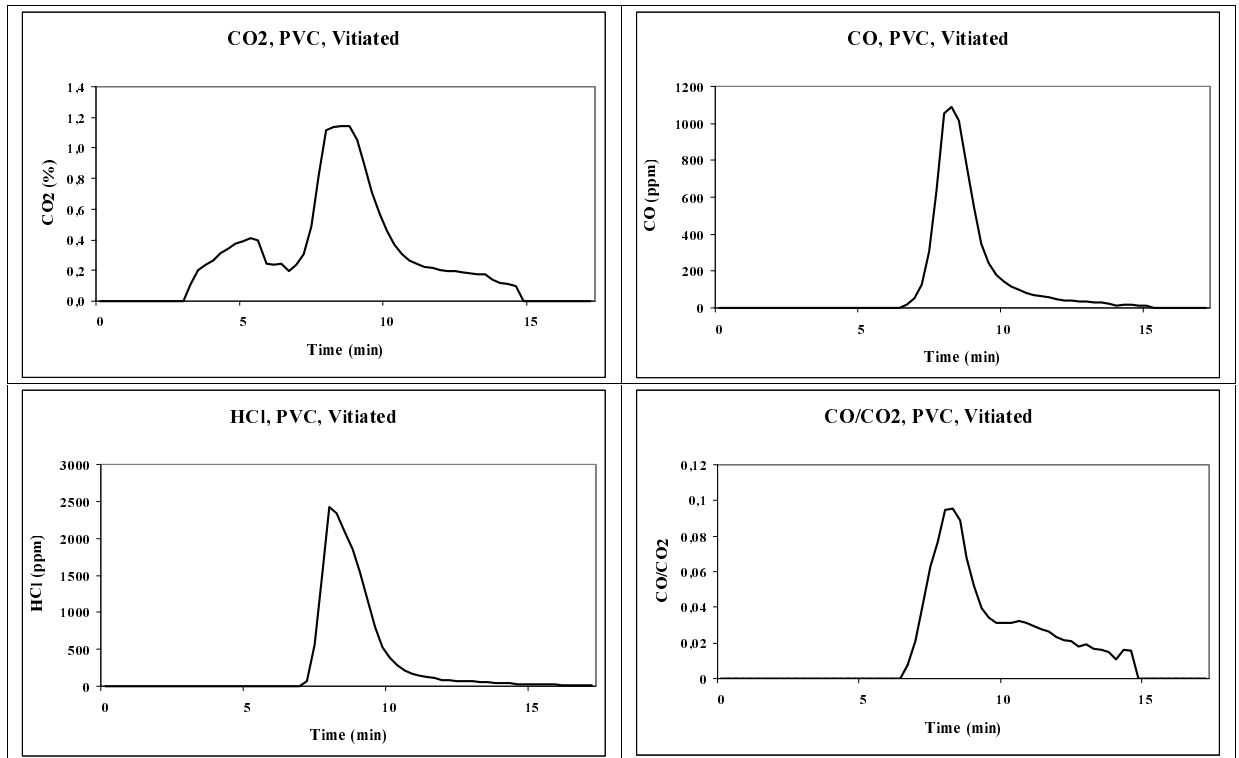


Figure 11 Product profiles of the gases detected during the vitiated experiment with PVC.

4.4.2 Results – CASICO experiments

The combustion gases that were found in the FTIR spectra collected during the analysis of the product gases from the experiments with the CASICO cable were H₂O, CO₂ and CO. The results of the quantification and the product profiles for H₂O are not presented here.

Well-ventilated

The airflow in this experiment was approximately 6500 l/min. A total of 15 cables, each 2.70 m long were mounted on one side of the cable tray with one cable diameter between each. A pre-measurement time of 2 minutes was applied. The gas to the burner was switched off after 10 minutes 30 s. The cable tray before the test weighed 27.4 kg and after the test 23.5 kg. The material collected in the kiosk weighed 1538 g, i.e. 2.4 kg material was burnt. The cable to the far left of the burner was only burnt on one side over a 30 cm distance. About 4 cm were not burnt on the rest of the cables. The HRR for this experiment is shown in Figure 12.

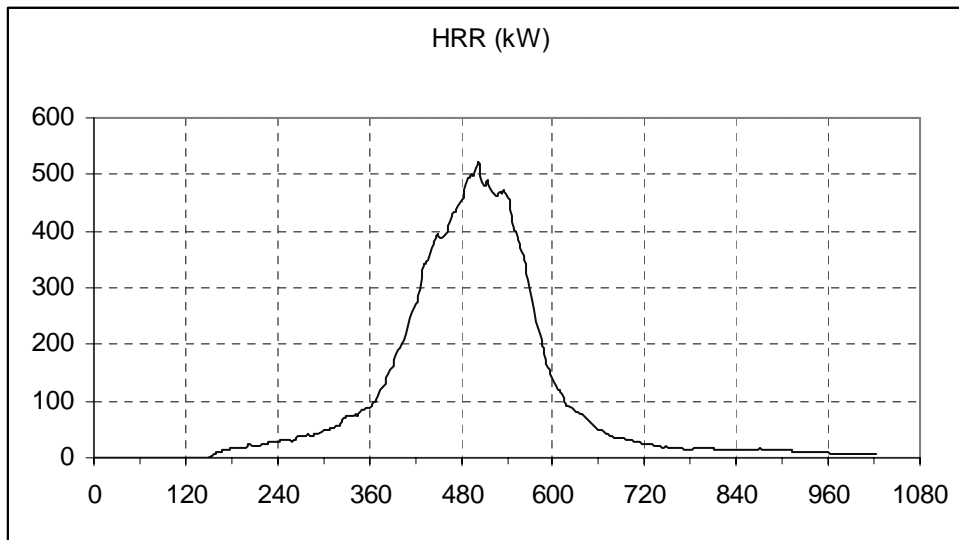


Figure 12 HRR for the well-ventilated CASICO experiment.

Subtraction of the CO₂ produced by the well-ventilated burner resulted in the amounts of combustion products summarised in Table 5.

Table 5 Quantified product gases after subtraction of CO₂ produced by burner from the well-ventilated experiment with CASICO.

		CO ₂ (burner subtracted)	CO
Weight combusted material (g)	2400,0		
Length burned (m)	39,90		
Total mass produced (g)		4675,27	26,57
Yield (g/g)		1,95	0,01
Yield (g/m)		117,2	0,67
Max g/s		22,14	0,31
Max concentration.		1,7 %	384,2 ppm

The species profiles for the species quantified using the FTIR are shown in Figure 13.

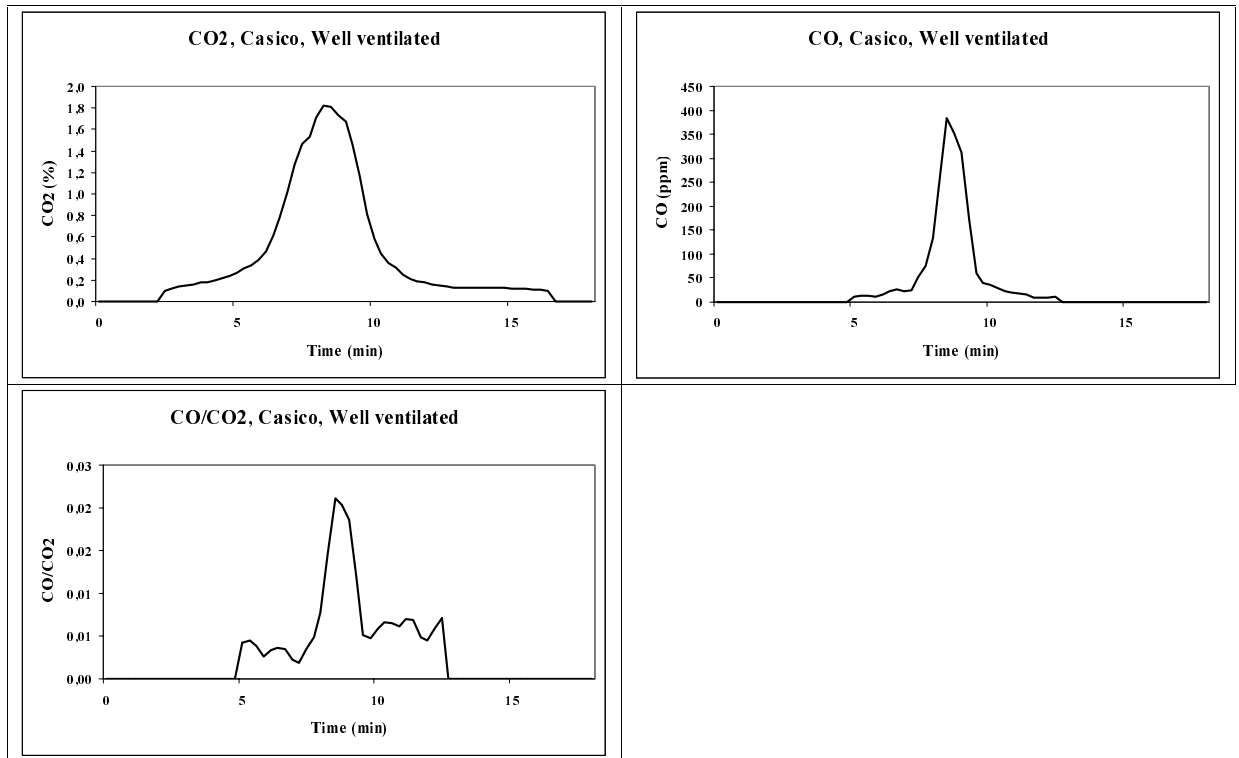


Figure 13 Product profiles of the gases detected during the well-ventilated experiment with CASICO.

Vitiated

No external airflow was used in this experiment. An extra burner was ignited 1 minute after start of measurement, the HRR of the burner was about 100 kW, and the burner was on for 2 and a half minute. The cable igniting burner was ignited 4 minutes after start of measurement. The burner was turned off 10 minutes after start of measurement. The measurement stopped after 20 minutes. The tray before the test weighed 27 kg and 23.1 kg after. A total of 1546 g material was collected at the floor, i.e. 2.9 kg material was burnt. The HRR for this experiment is shown in Figure 14.

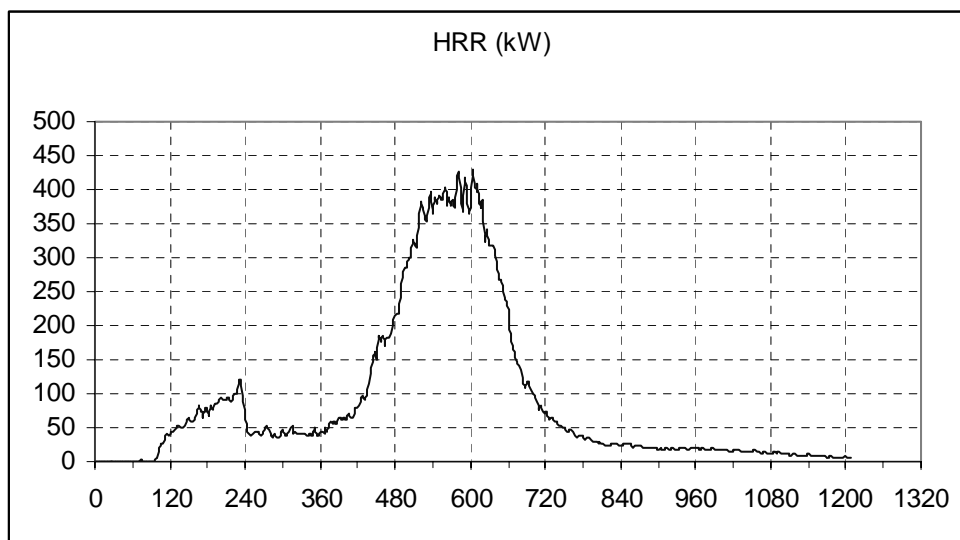


Figure 14 HRR for the "vitiated" experiment with the CASICO cables.

Subtraction of the CO_2 produced by the well-ventilated burner resulted in amounts of combustion products shown in Table 6.

Table 6 Quantified product gases after subtraction of CO_2 produced by burner from the Vitiated2 experiment with CASICO.

		CO_2 (burner subtracted)	CO
Weight combusted material (g)	2900,0		
Length burned (m)	40,50		
Total mass produced (g)		4751,38	117,60
Yield (g/g)		1,64	0,04
Yield (g/m)		117,3	2,90
Max g/s		16,69	1,36
Max conc.		1,3 %	1683,3 ppm

The product profiles of the gases detected can be seen in Figure 15.

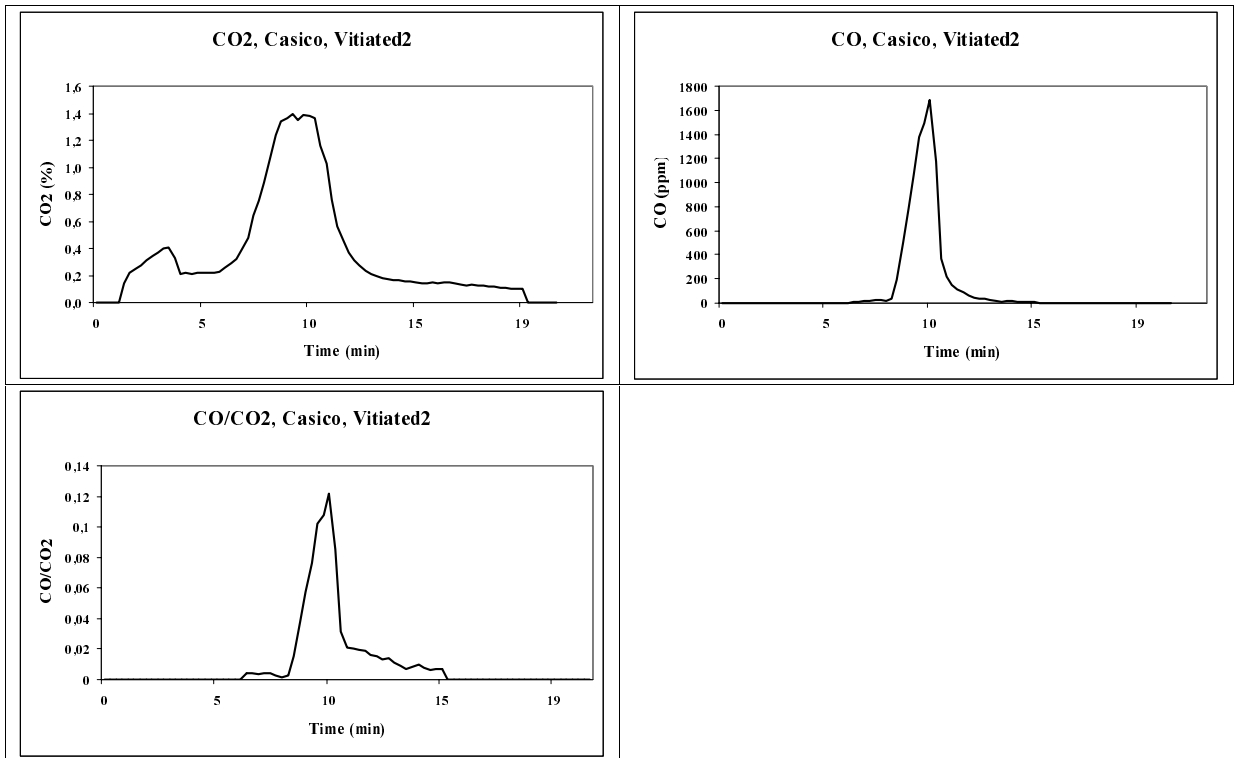


Figure 15 Product profiles of the gases detected during the Vitiated experiment with CASICO.

The concentration of CO reached a peak-value approximately 4 times higher than the peak-value of CO reached in the well-ventilated experiment. The CO/CO_2 ratio reached a maximum value about 50% greater than the maximum value for the ratio reached in Vitiated1. The maximum CO/CO_2 ratio for this experiment was about 5 times greater than the ratio for the well-ventilated experiment. This indicates that a more vitiated

atmosphere was reached than in the well-ventilated experiments. It is, however, difficult to say how vitiated the atmosphere was when the second burner was ignited.

4.4.3 Organic Species Chemical Analyses

A number of detailed chemical analyses were conducted in conjunction with the large scale experiments. These are summarised in Table 7 to Table 9, below.

Table 7 Chemical analysis of 20 different PAHs in fire gases from IEC 332-3 experiments. Yields as $\mu\text{g}/\text{m}$ burned cable.

Substance	amu	blank (propane only) *	CASICO, well ventilated	CASICO, vitiating	PVC, well ventilated	PVC vitiating
Acenaphthylene	152	10	2600	6300	9100	5800
Acenaphthene	154	0,5	33	2000	99	97
Fluorene	166	1,8	410	810	1500	970
Phenanthrene	178	19	1300	3600	8300	7000
Anthracene	178	2,0	230	440	1300	810
Fluoranthene	202	6,8	490	1200	2700	2200
Pyrene	202	6,0	560	1200	1200	740
Benzo(a)fluorene	216	0,3	35	28	260	190
Benzo(b)fluorene	216	0,1	23	41	250	170
Benzo(a)anthracene	228	0,6	38	140	990	660
Chrysene/Triphenylene	228	1,0	120	210	1200	1000
Benzo(b)fluoranthene	252	1,3	90	410	1700	1300
Benzo(k)fluoranthene	252	0,4	45	140	310	220
Benzo(e)pyrene	252	0,6	60	220	560	430
Benzo(a)pyrene	252	0,5	22	170	440	280
Perylene	252	0,1	0,9	26	19	11
Indeno(1,2,3-cd)pyrene	276	0,8	87	360	670	430
Benzo(g,h,i)perylene	276	0,8	83	370	440	270
Dibenzo(a,h)anthracene	278	0,2	4,5	20,0	150	130
Coronene	300	2,1	49	210	200	120
Sum of all 20 PAHs		55 *	6300	16000	31000	23000

* 40 m cable assumed in yield calculation.

Table 8 Chemical analysis of dibenzodioxins and -furans in fire gases from IEC 332-3 experiments. Yields as ng/m burned cable.

Substance	blank (propane only)*	CASICO, well ventilated	CASICO, vitiated	PVC, well ventilated	PVC, vitiated
DIOXINS					
2378 TCDD	N.D.	N.D.	N.D.	N.D.	N.D.
Sum of TCDD	N.D.	N.D.	N.D.	N.D.	N.D.
12378 PnCDD	N.D.	0,68	1,4	21	16
Sum of PnCDD	4,13	23	41	44	50
123478 HxCDD	0,20	1,2	2,3	3,9	5,4
123678 HxCDD	0,53	2,2	4,8	6,8	8,9
123789 HxCDD	1,1	2,5	4,8	5,2	7,8
Sum of HxCDD	9,0	27	52	71	85
1234678 HpCDD	2,7	13	29	40	47
Sum of HpCDD	4,9	25	52	79	93
OCDD	4,9	18	34	75	62
FURANS					
2378 TCDF	0,53	4,5	7,0	63	93
Sum of TCDF	24	120	160	2600	2700
12378 PnCDF	0,53	3,6	5,6	95	93
23478 PnCDF	1,3	8,7	14	170	160
Sum of PnCDF	15	68	110	1900	1500
123478 HxCDF	1,0	4,5	6,7	170	130
123678 HxCDF	1,1	4,9	6,7	170	140
234678 HxCDF	1,9	8,7	17	210	170
123789 HxCDF	0,56	4,1	8,2	150	120
Sum of HxCDF	15	53	85	1700	1200
1234678 HpCDF	4,5	18	27	630	370
1234789 HpCDF	0,79	3,4	6,3	210	130
Sum of HpCDF	5,3	29	44	1100	660
OCDF	5,6	19	21	440	220
TCDD-equivalents I-TEQ, minimum	1,4	8,7	15	190	167
TCDD-equivalents I-TEQ, maximum	2,3	9,8	17	190	171

* 40 m cable assumed in yield calculation.

N.D. = indicates that the value was below the level of quantification.

Table 9 Chemical analysis of VOC including formaldehyde in fire gases from IEC 332-3 experiments. Yields (mg/m cable) of dominating single compounds and as total amount, "TVOC" (all as toluene equivalents except formaldehyde)

Substance	CASICO, well ventilated	CASICO, vitiated	PVC, well ventilated	PVC, vitiated
formaldehyde *	N.D.	65	N.D.	N.D.
benzene	37	190	130	100
toluene	2,9	15	16	13
chlorobenzene	N.D.	N.D.	6,5	4,4
ethynylbenzene (=“phenyl acetylene“)	1,6	2,7	12	13
styrene	2,5	12	11	9,4
phenol	1,5	15	N.D.	N.D.
indene	1,5	5,3	2,8	3,8
naphthalene	6,8	26	34	30
undefined VOCs	2,0	12	23	26
TVOC (excluding formaldehyde)	56	270	230	200

* measured by a specific method

N.D. = indicates that the value was below the level of quantification.

4.4.4 Conclusions

The experimental design succeeded in lowering the amount of oxygen in the fire test rig, making the atmosphere present more vitiated. The degree of vitiation is, however, difficult to determine. The CO/CO₂-ratios calculated from the analysis results received during the experiments is not especially large. The largest difference is found when comparing the results from the well ventilated and vitiated experiments with the CASICO cables. The peak value of the CO/CO₂-ratio for the vitiated experiment was about 5 times greater than the peak value of the ratio calculated for the well-ventilated experiment. The peak value of this ratio for the vitiated experiment was, however, only about 0.13. Indications from previous large scale room experiments conducted as a part of the TV Fire-LCA case study indicate that in large scale experiments the CO/CO₂ ratio does not necessarily come close to 1 in vitiated experiments.

The difference between the CO/CO₂-ratios calculated from the results from the well ventilated and vitiated experiments on the PVC-cables is very small. The ratio for the vitiated experiments is only about 25% higher than the ratio for the well ventilated. This is, however, probably explained by the fact that chlorine is present in the PVC cable. The chlorine acts as combustion inhibitor, reducing the production of CO₂, and thus increasing the amount of CO produced even under well ventilated scenario. Thus, when performing the experiment in a vitiated atmosphere, the increase in the production of CO is not as large as in the CASICO cable experiments. This was also predicted based on the results of the small scale experiments (see previous section).

The yield of HCl produced from the PVC cables was higher in the well ventilated experiment than in the vitiated. This difference could not be predicted based on the results from the small scale experiments.

Some photographs from the large scale experiments are shown in Appendix 1.

4.5 References

- 1 DIN 53 436
- 2 Smith-Hansen, Lene, “Toxic Hazards from Chemical Warehouse Fires”, Final Report from TOXFIRE study, RISÖ National Laboratory, Roskilde, Denmark, Risö-R-713 (EN).
- 3 Viktor Emanuelsson, Heimo Tuovinen and Margaret Simonson, “Formation of Hydrogen Cyanide in Room Fires”, SP Rapport 2000:27
- 4 Hakkarainen, T., “Smoke gas analysis by Fourier transform infrared spectroscopy – The SAFIR project “, Research Note 1981, Espoo: VTT Technical Research Centre of Finland (1981).

5 Fire-LCA Model – Results

5.1 Scenario descriptions

As described previously in this report the Cables Fire-LCA model defined within this study has endeavoured to compare two products with equivalent fire behaviour. In this context, the end-of-life (EOL) scenarios have been deemed to be very important to the outcome of the model. At present the majority of cable waste is either left in building (i.e. disconnected but not removed) or sent to Landfill in lieu of a better alternative.

A number of future alternatives have, however, been identified as important to investigate. The four EOL scenarios that have been selected for detailed study are:

Scenario 1: 100% landfill plastics and copper

Scenario 2: 100% landfill plastics, 100% material recycling copper

Scenario 3: 100% energy recovery plastics, 100% material recycling copper

Scenario 4: 100% material recycling plastics, 100% material recycling copper

These scenarios have been selected to focus on extreme situations. In real life one would expect a percentage of material to go to recycling in some form, which would be less than 100 % but more than 0 %.

Detailed results are presented for the energy use for the model and the emission of a number of key species to the air are presented for all scenarios. The results are presented to best allow comparison between the various scenarios for the same product but do also allow comparison between the products within each scenario.

Effort was expended to obtain information concerning well-ventilated and vitiated combustion products from the large-scale experiments for use in different parts of the LCA model. In the cases where the cables are involved in a larger fire (i.e., all secondary fires, all “Cable-room” fires and all “Cable-house” fires) the vitiated information was used. In the case where the cables were involved in fires that did not spread beyond the object of origin then the opportunity to use well-ventilated cable fire information was available. A comparison was made between the results for scenario 1 depending on whether vitiated data is used throughout or well-ventilated data has been used for the “Cables only” category in the Fire-LCA model. This comparison yielded very little difference and has not been included in the report. Based on this comparison the vitiated emission results have been used for all cable fires.

The life time for a cable is varied but based on literature information ^{1,2} an average life time of 30 years has been selected. It has been suggested within the project group that installation cables in typical dwelling applications may have a longer life time and the effect of choosing a 50 year life time has also been investigated.

Further, as the fire model used for the two cables in this study is the same we have made a comparison between the results with and without the influence of the Fire modules for the first scenario.

In this study, an effort has also been made to investigate the uncertainty in the results calculated using this model.

5.2 Energy Use and Emissions

Please note that in all figures in section 5.2 “Cable prod.” includes production of replacement cables while “Repl. Prod.” includes production of all replacement material other than cables. In all cases, the categories shown in the bar charts have been selected such that they are visible on the diagram. In cases where the emission is too low to be visible, the category has not been included.

5.2.1 Energy use

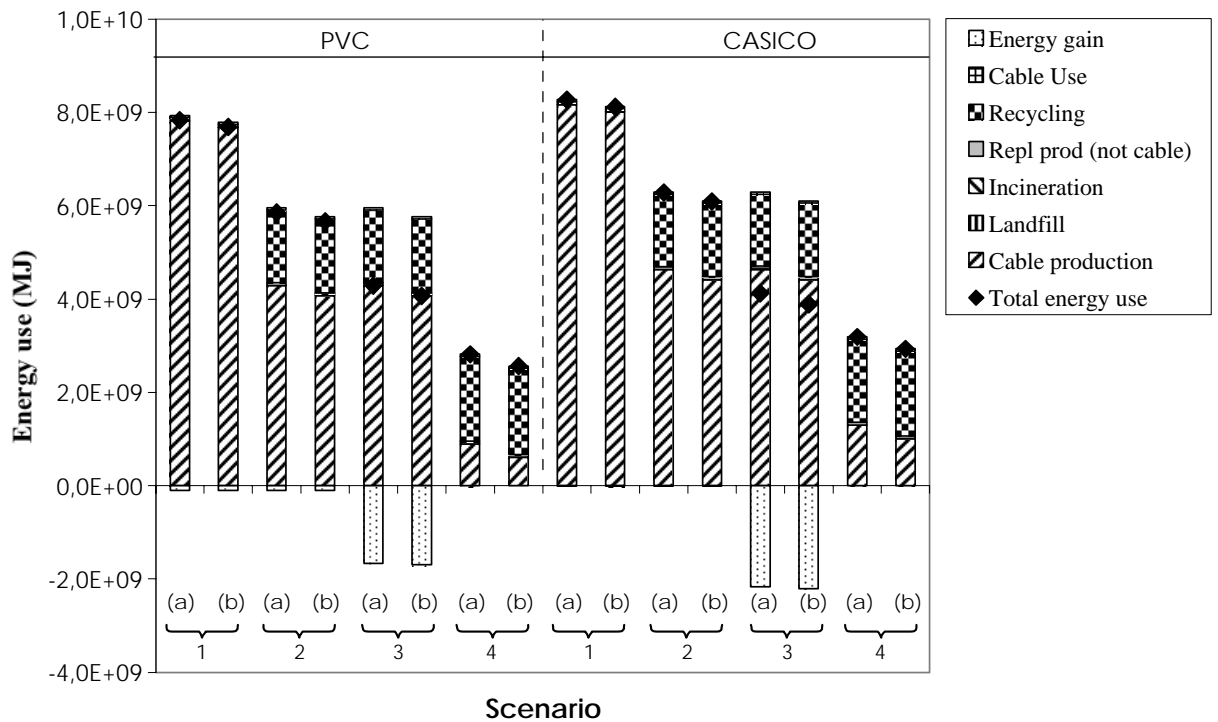


Figure 16 Use of energy resources for PVC and CASICO cables, 30 year life-cycle. The division is based on the part of the model the energy is required or produced. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

As seen in Figure 16, the energy use of the different scenarios decreases for each scenario, with the highest energy consumption for Scenario 1 and the lowest consumption for Scenario 4.

The energy consumption of the CASICO cable is higher than the energy consumption of the PVC cable for Scenario 1, 2 and 4. The majority of energy is used during the production of the cable in Scenario 1 through 3 for both the cables, as seen in Figure 16. When the thermoplastic recycling is started in Scenario 4, the Recycling stage is the most energy consuming stage. Recycling is also important in Scenario 2 and 3, but when the thermoplastic recycling is started in Scenario 4, it becomes the dominant energy consumer in the life cycle of the cable.

The energy gain for PVC in Scenario 1 and 2 comes from the production of CH_4 in landfills, where the CH_4 is collected and can be used as an energy source. The energy gain for the CASICO material in Scenario 1 and 2 is, due to a small production of CH_4 , much

smaller than the gain from PVC. In Scenario 3, however, the Energy gain is larger for the CASICO cable than for the PVC cable, due to the higher amount of energy recovered through incineration, as the energy content of the CASICO material is higher than that of the PVC material.

5.2.2 CO-production

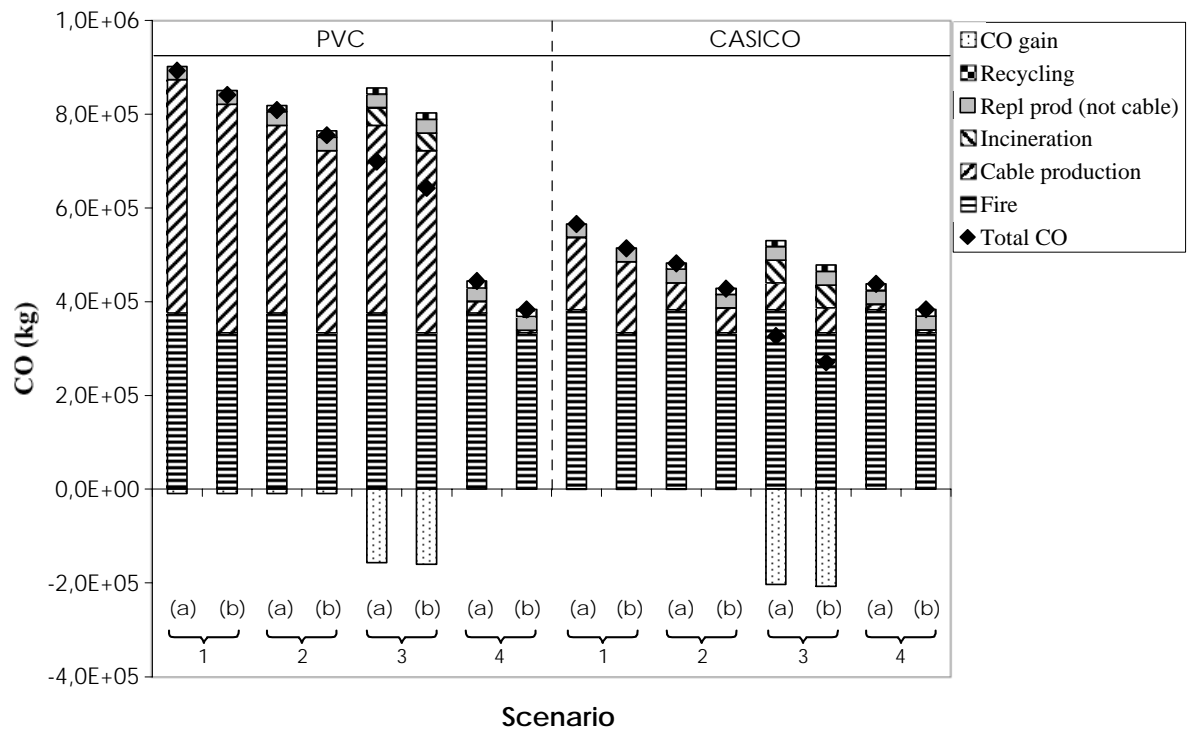


Figure 17 CO emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

As seen in Figure 17, there is a large difference in the production of CO between the two materials in Scenario 1 through 3. In these scenarios, the production of CO from PVC is much higher than the production from the CASICO cable. In scenario 4, however, the production of CO is fairly equal, with a production of CO from the CASICO cable that is only slightly higher (approximately 1,5%) than the production from the PVC cable.

The amounts of CO produced in fires are almost equal for both materials in each of the scenarios investigated. CO produced from other parts of the life cycle of the cables, however, differs significantly. As seen in Figure 17, CO produced during cable production is very important for the PVC material in Scenario 1 through 3. This module in these scenarios is the largest source of CO, producing about 50% of the total CO. In Scenario 4, however, the production is reduced considerably. In this case, the CO from cable production is only responsible for about 6% of the total production. This is due to material recycling of the plastics from the cables, thereby decreasing the demand for virgin cable plastic material. The amount of CO being produced due to fires (either as direct emission or due to the replacement of material) in Scenario 4 is about 90% of the total production of CO.

In the case of the CASICO material, fire is the largest source of CO in all scenarios. The second largest source of CO in Scenario 1 through 3 is cable production. When comparing the amounts of CO produced from each of the parts of the life cycles of the two materials the largest difference between the results of the materials is found when comparing the results for the cable production. In this part of the model, the production

of CO from PVC is much higher than that from the production of the CASICO cables. The other parts of the life cycles of the cables are quite similar.

The CO gain from incineration of the CASICO material in Scenario 3 is high, reducing the amount of CO produced in this scenario considerably. The gain for the CASICO material is larger than the gain for the PVC material in Scenario 3. Thus, the difference between the two materials in Scenario 3 is very large. The CO gain recovered during the incineration of the CASICO cables in Scenario 3 results in the lowest production of CO of all of the scenarios investigated. The gain received from landfills, however, is larger for the PVC material than for the CASICO material, due to the greater production of CH_4 from PVC during its decomposition process, resulting in an energy recovery that is larger than the energy recovery from the CASICO cable.

5.2.3 CO₂-production

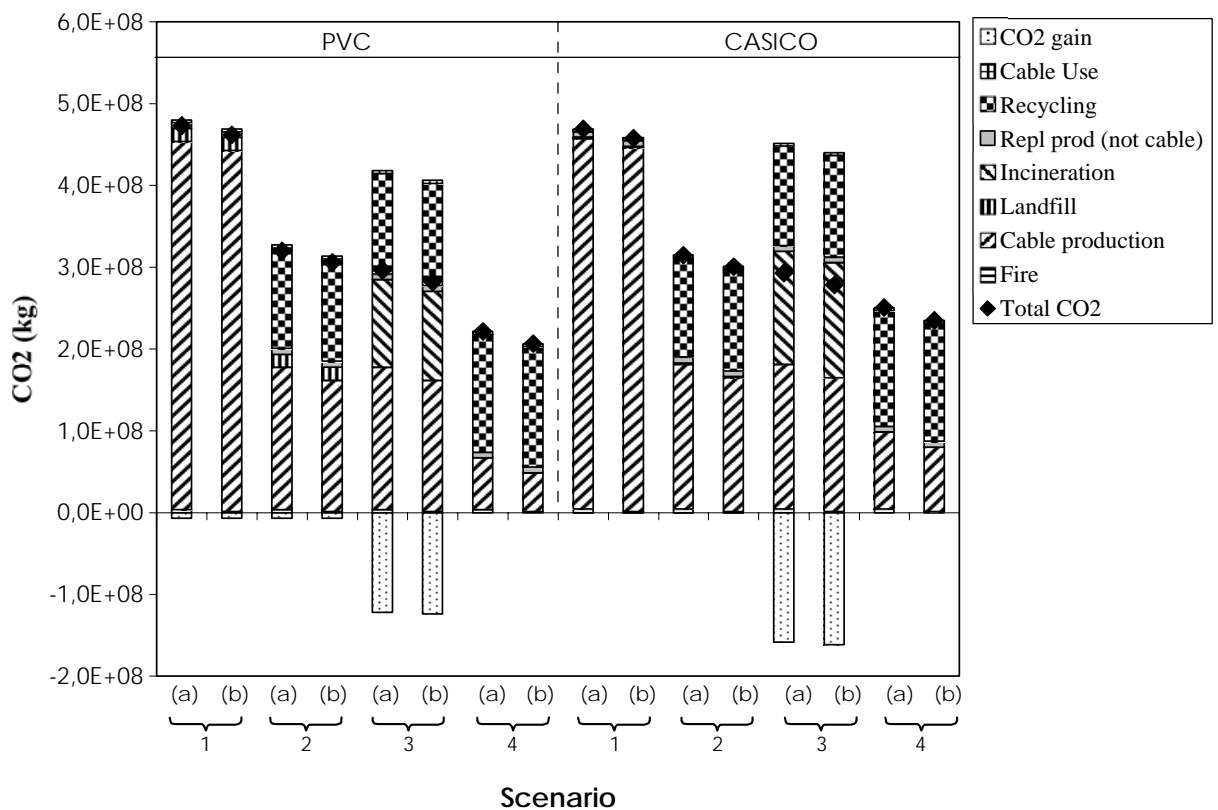


Figure 18 CO₂ emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

The total production of CO₂ from the materials is quite similar, as shown in Figure 18. In Scenario 3 the total production of CO₂ is almost equal, due to the CO₂ gain the CASICO cable “earns” through the incineration process.

The production of CO₂ in Scenario 1 is dominated by CO₂ from cable production (93% in PVC and 96% in CASICO). The main source of CO₂ in cable production is copper production (60% for both of the materials). When the copper recycling is started in Scenario 2, the CO₂ production is decreased drastically, as seen in Figure 18. The CO₂ production from recycling mainly comes from the production of electric power in the

recycling processes, but a small part also comes from copper recycling. In Scenario 3, where incineration is used, the total production of CO₂ from the incineration part of the life cycle can be considered to be negative for both the cables. This can actually happen because the emission of CO₂ from the incineration is smaller than the CO₂ that would be produced if the same amount of energy that is produced in the incineration module had been produced using another process. In the LCA model an oil boiler, which uses crude oil, is used to estimate the emissions of CO₂ that are “earned” by using incineration. This “earned” amount is subtracted from the total amount of CO₂ produced during the whole life cycle of the cable. As stated previously, the emissions of CO₂ from the oil boiler would, in fact, be larger than the actual amount of CO₂ emitted from the incineration module, thus resulting in a negative amount of CO₂ emitted from the incineration process.

In Scenario 4, the largest part of the CO₂ is produced during recycling for both of the materials. This part is of the life cycle causes approximately 60% of the total production of CO₂, where the production of energy used in the recycling is the largest source of the emissions of CO₂.

The amount of CO₂ produced in fires compared to the total amount emitted is very low, only ranging between 1 and 4% of the total amount of CO₂ produced in the scenarios investigated.

5.2.4 Hydrocarbon (HC)-production

The total production of HCs is dominated by emissions from the production of the cables as seen in Figure 19. Approximately 70% of the total production of HCs from PVC in Scenarios 1 through 3 comes from the cable production, with 40% of the total cable production coming from the production of the PVC polymer. Due to the importance of the production of PVC, the production of HCs from Scenarios 1, 2 and 3 is almost equivalent. In Scenario 4, however, the production is decreased with about 60%, due to the recycling of the PVC plastics.

The production of HCs from the CASICO material is approximately 100% higher than the total emissions of HCs from the PVC cable. The cable production is very important in this case too, being responsible for about 85% of the total amount produced. Specifically, the production of EBA is responsible for about 80% of the total production of HCs. As seen in Figure 19, the production of HCs from Scenario 4 exhibits a similar behaviour to that of the PVC cable, due to the importance of the material recycling to the cable production stage.

The importance of the production of HCs from fires in Scenarios 1 through 3 differs between the two materials. In Scenarios 1 through 3, fires are responsible for about 10% of the total amount of HCs produced by the PVC cable, and for about 5% of the total amount of HCs produced by the CASICO cable. In Scenario 4, however, the importance is much larger (approximately 26% for both the materials). If the emissions of HCs from fires and from the production of replacement products (not cable) in Scenario 4 are added together, fires are responsible for about 60-70% of the total emissions of HCs. In the other scenarios this production (Fire+production of replacements) corresponds to about 25 % of the production from the PVC cable and about 13 % of the production from the CASICO cable. The production of HCs from fires, however, is naturally equally large in all of the scenarios (although it differs between the two systems), but the importance of fires increases as the production of HCs from other sources decreases.

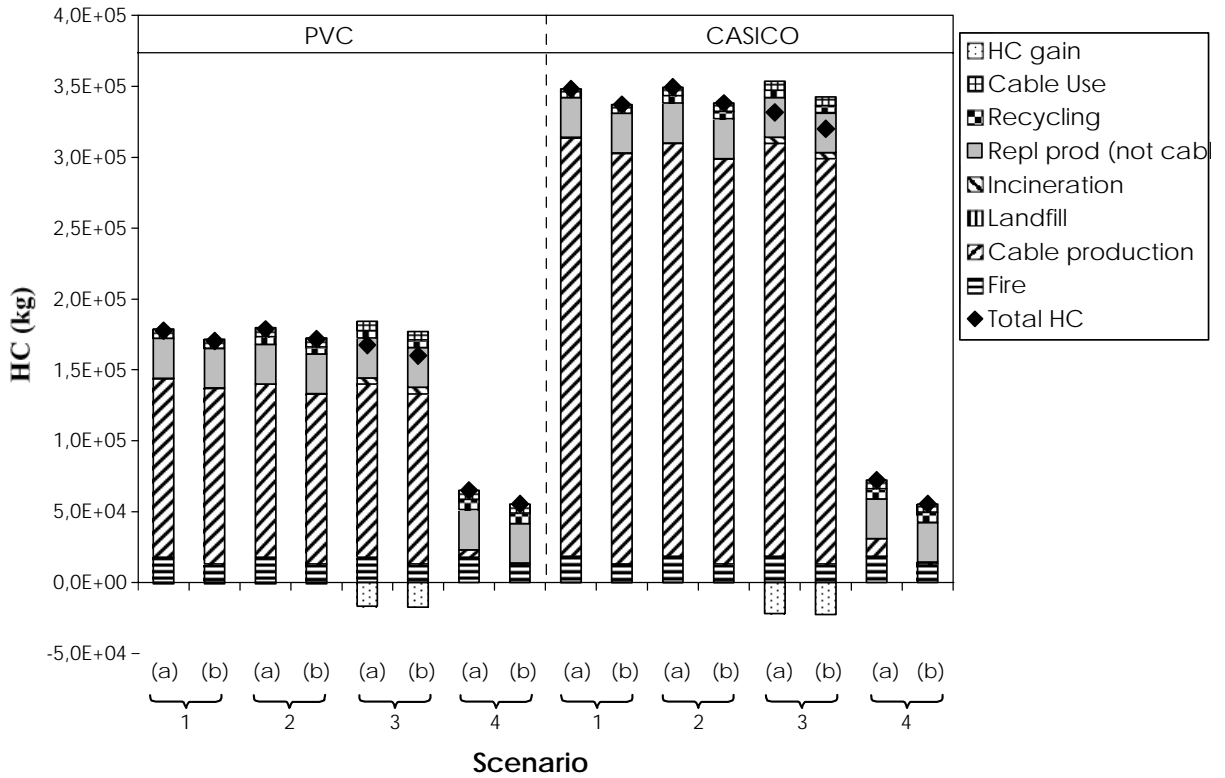


Figure 19 HC emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

5.2.5 NO_x-production

As seen in Figure 20, the dominating source of NO_x for both of the cables in Scenarios 1 through 3, is the emissions caused by the cable production. About 95% of the total production of NO_x in Scenario 1 comes from these parts. When copper recycling is started in Scenario 2, the production of NO_x from cable production is reduced considerably, as the largest source of NO_x during the production of the cables is the production of copper. In Scenario 2, the polymer production becomes the largest source of NO_x , being responsible for about 56%. In Scenario 4, when material recycling of the cable plastics is started, the production of NO_x decreases further, the largest part of the total emission coming from the recycling part where the largest part of the NO_x production is produced during the recycling of copper.

During the fire tests, the concentration of NO_x in the fire gases did not exceed the detection limit of the analysis equipment. Due to this, no input for the emissions of NO_x from cable fires, room fires and house fires were used in the LCA model. Therefore, the only NO_x originating from fires in the LCA model is produced during production of replacement material (not cable) to material that was destroyed in fires. This part of the life cycle model is responsible for from 3 % of the total emissions of NO_x in Scenario 1 up to about 11 % in Scenario 4.

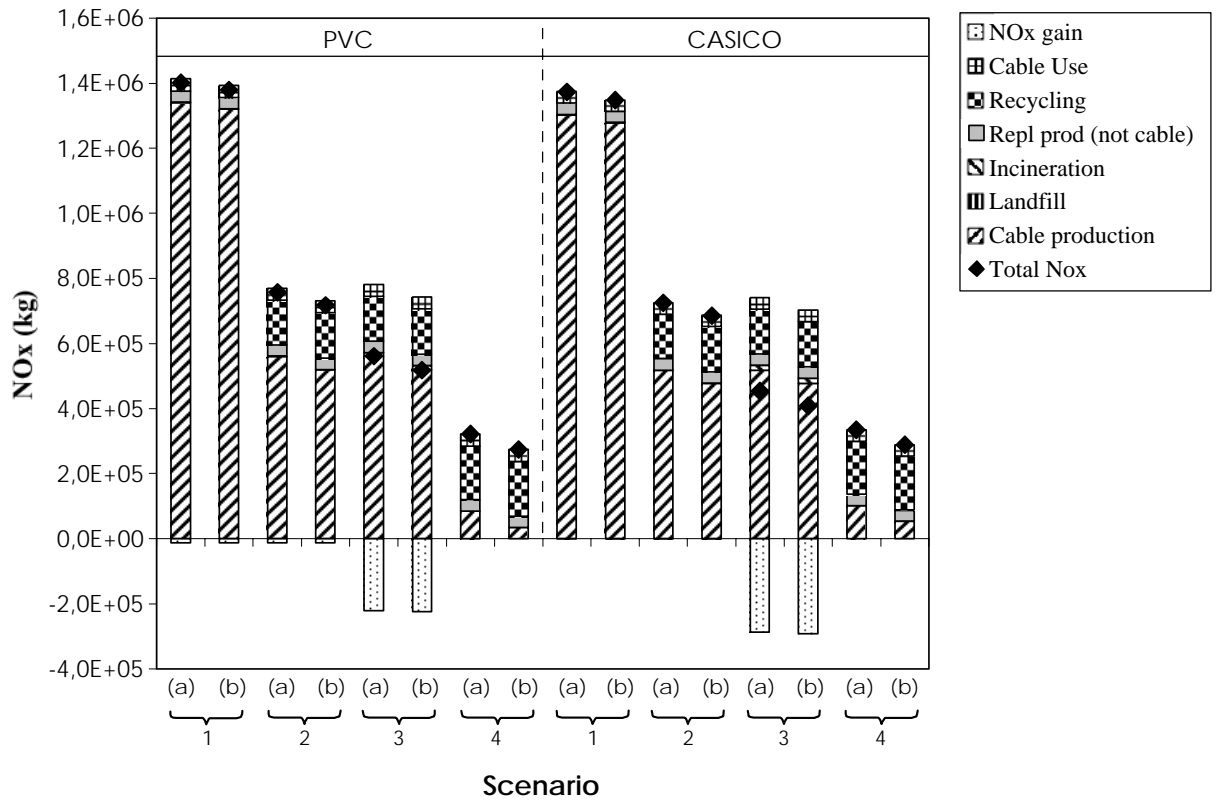


Figure 20 NO_x emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

5.2.6 SO_2 -production

As seen in Figure 21, almost all the SO_2 that is produced during all the scenarios for both of the materials is produced during the production of the cables. In fact, about 99% of the total amount of SO_2 produced in Scenario 1 is caused by the production of copper. The production in Scenario 2 through 4 is much smaller than the production in Scenario 1 (~5-6% of the total production in Scenario 1), as copper is recycled in Scenarios 2 through 4.

The fire part of the emissions of SO_2 is quite small, but it comes in second place after Cable production in all of the scenarios for both of the materials. The part of the emissions is about 0,5% for Scenario 1, but increases to about 8% in Scenario 2 and 3, and to about 10% in Scenario 4.

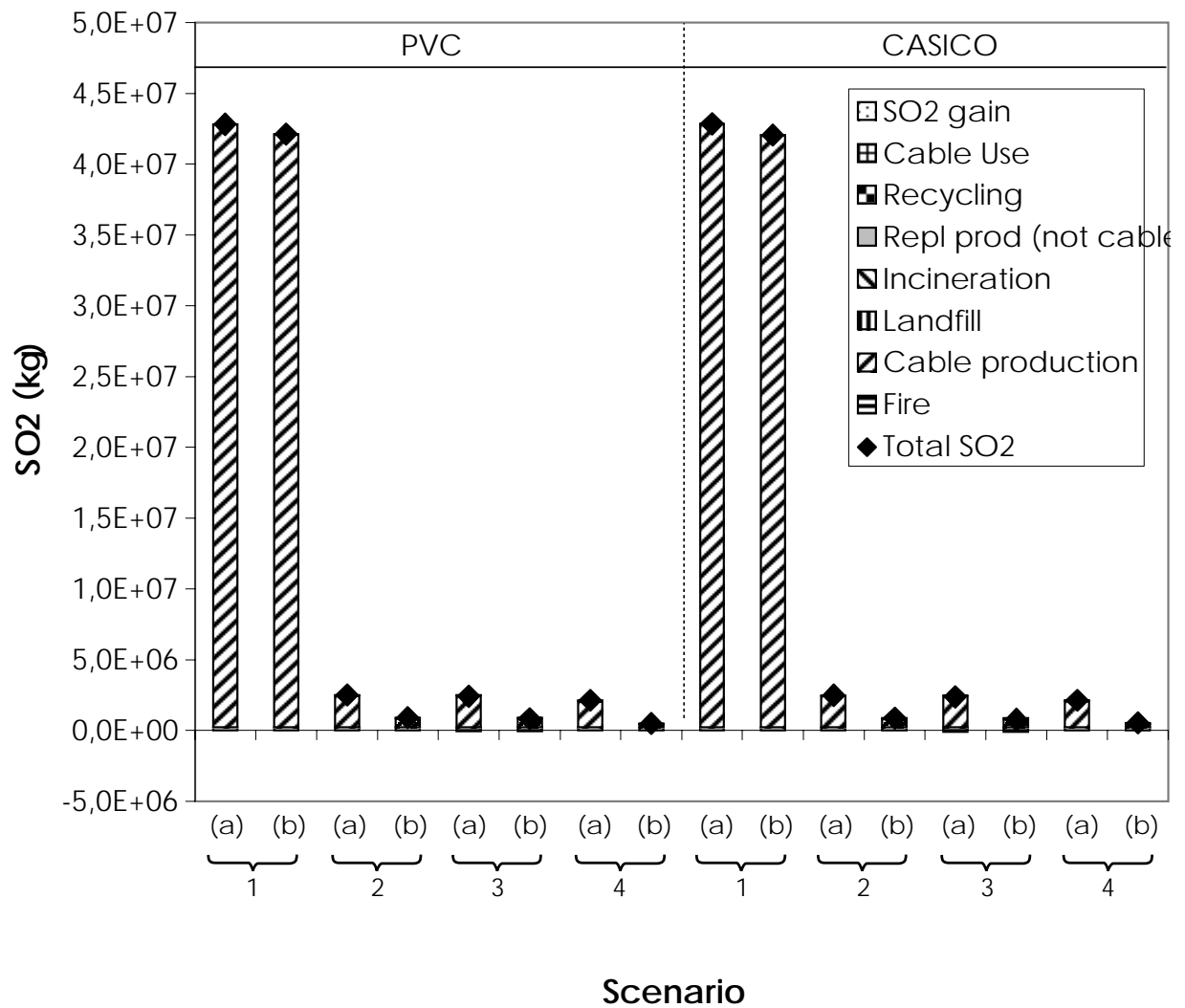


Figure 21 SO₂ emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

5.2.7 TCDD-equivalent production

Fire is the largest producer of dioxins for both of the materials. This is partly due to fires being one of the few areas in the model where detailed information concerning the emission of dioxins is available. This is probably a sound reflection of the most important sources of dioxins, however, as most other sources are bound to be minor (emission from energy production and energy recovery modules are included). Dioxins from the fire experiments with the CASICO material were due to a small amount of chlorine present in the plastic material. The chlorine was present in such a small quantity that it probably is a contaminant in, for example, the filler material. Its presence has, however, been confirmed through elemental analysis of the cable material.

The largest production of dioxin is from Scenario 3, for both of the materials, due to the production occurring during the incineration process. The increased production of dioxins from the CASICO material in Scenario 3 is, however, almost negligible (only 0,6% of the total production in Scenario 1, 2 and 4). In Scenario 1, 2 and 4, fires are the only source of dioxins for the CASICO material, since no dioxins are emitted during the production of the cables. The total production of dioxins from the CASICO material is

approximately 1/10 of the dioxins produced from the PVC material, except for Scenario 3, where the total production is only 6% of the total production from the PVC material. Very small amounts of dioxins (in fact near 0,0% of the total production) are emitted during the production of the PVC material. This production decreases in Scenario 4, due to decreased production of PVC plastics. Due to the large production from fires, however, the difference in the total production of dioxins between the scenarios (except Scenario 3) is negligible. The only producer of dioxins for the CASICO material in Scenario 1, 2 and 4 is fire, thus no difference can be seen between these scenarios. In Scenario 3, the increase of emissions of TCDD's due to the incineration is very small, resulting in a total emission of TCDD that is almost equal with the emissions from the other scenarios that has been examined. Thus, no significant difference can be seen between the scenarios studied with the CASICO cable.

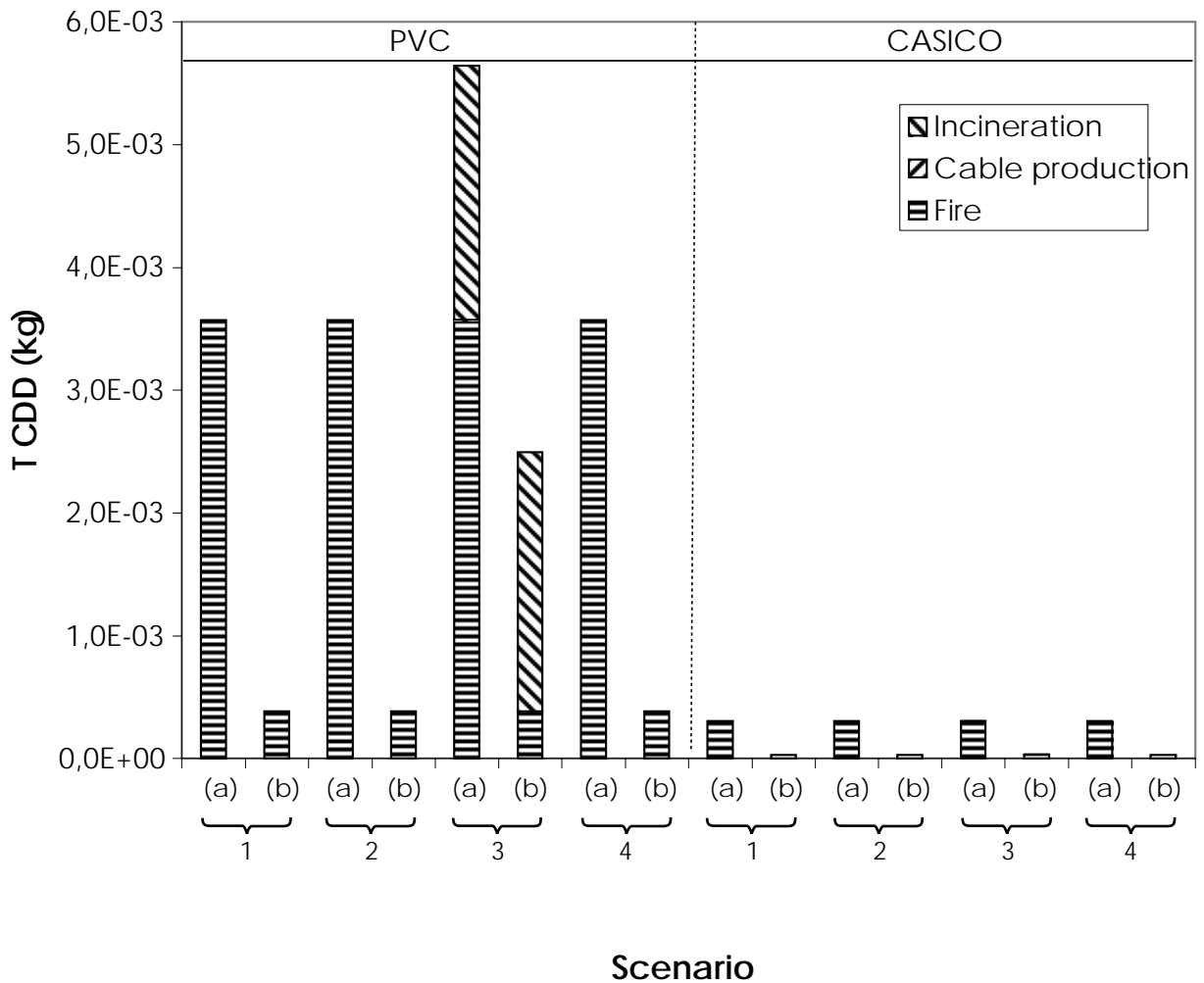


Figure 22 TCDD-equivalent emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

5.2.8 Hydrochloric acid (HCl)-production

As seen in Figure 23, the production of HCl from the PVC cable is much larger than the production from the CASICO cable. The HCl from the CASICO cable is emitted during the Cable production and the production of replacements of equipment destroyed in fires,

but compared to the PVC cable the total production of HCl from the CASICO cable is insignificant (approximately 0,5% of the total production of HCl from the PVC cable).

The dominating source of HCl from the PVC cable in scenario 1, 2 and 4 is fires, but in Scenario 3 about 58% of the total production of HCl comes from the incineration process. This is based on an assumption that the emissions are maintained within the legal limit.

The emissions of HCl from the production of replacements and the cable production are very low compared to the production from fires for the PVC cable. The emissions during the production of replacements are less than 0,1%, and the production from the cable production is about 1%.

Regarding the CASICO cable, the dominating source of the HCl emissions is the cable production. Since possible HCl production was below the detection limit of our analysis method, no HCl emission from fires is included in the LCA model describing the CASICO cable. In Scenario 4 the cable production decreases as the recycling increases, thus the production of HCl from the cable production decreases, increasing the importance of the production of replacements as a source of HCl.

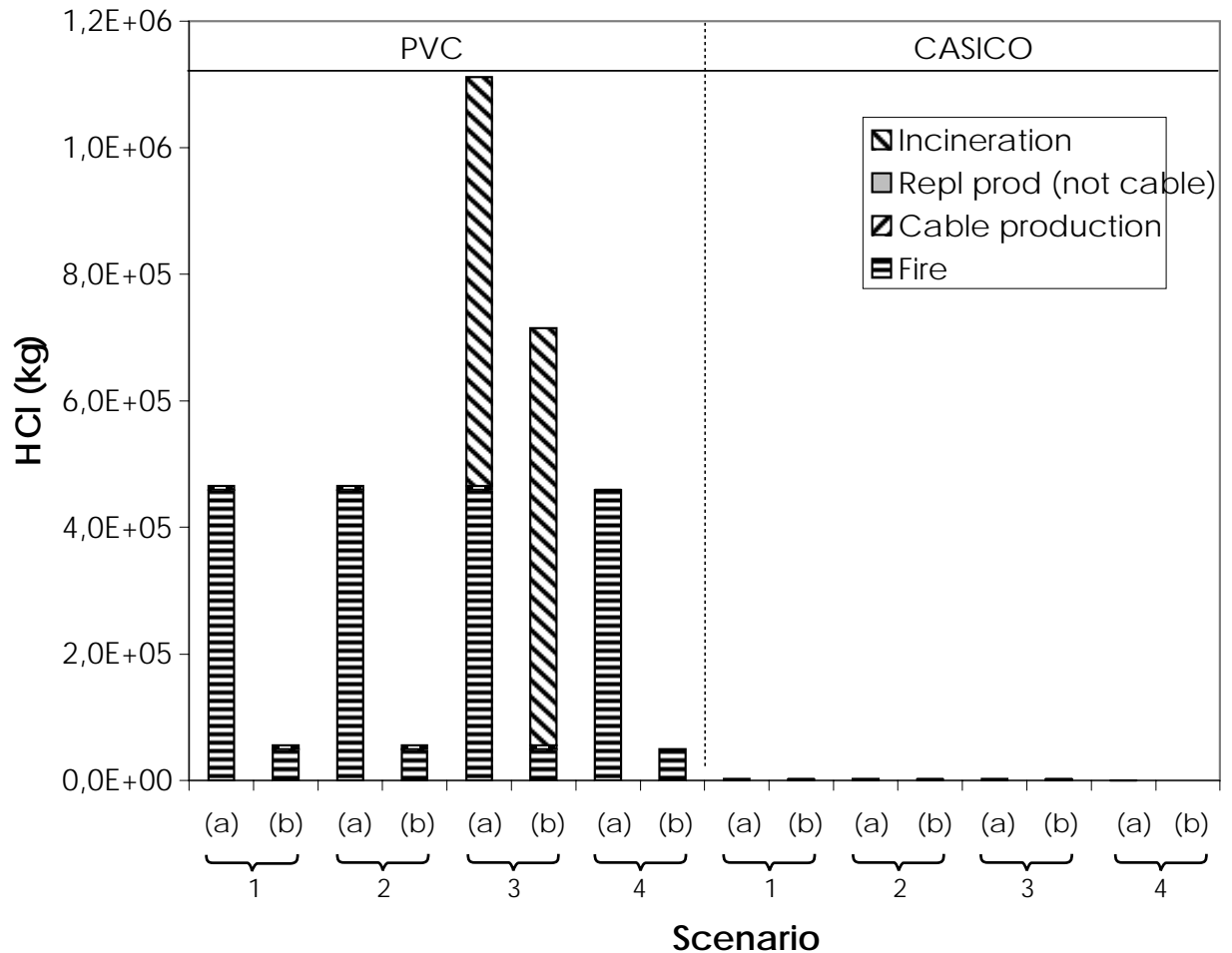


Figure 23 HCl emission to air for PVC and CASICO cables, 30 year life-cycle. The bars are coded to show the amount from the various parts of the model. The results are shown for (a) 100 % secondary fires and (b) 10 % secondary fires for each scenario.

5.3 Results with 30 and 50 years lifetime

The average lifetime of electric cables was estimated to be 30 years, and this number was used in the LCA model. In recognition of the fact that the average life of an installation cable could well be greater than 30 years we have investigated the importance of the choice of the lifetime. Thus, a lifetime of 50 years has also been investigated. In this section, the results of the 50 years lifetime scenario are compared with the results of the 30 years lifetime scenario. The model that was investigated was Scenario 1, i.e. 100% of the cables were placed in landfills at their end of life with the exception of those cables that were destroyed in fires. The results of this comparison are shown in Figure 24. The comparison in this figure is normalised relative to the 30 year scenario. The absolute values are summarised in Table 10.

The difference between the two scenarios investigated is that more cables are consumed in fires during 50 years than during 30 years. The only factors that are changed in the model are therefore constants that increase the amounts of cables being destroyed in fires. No other changes are made.

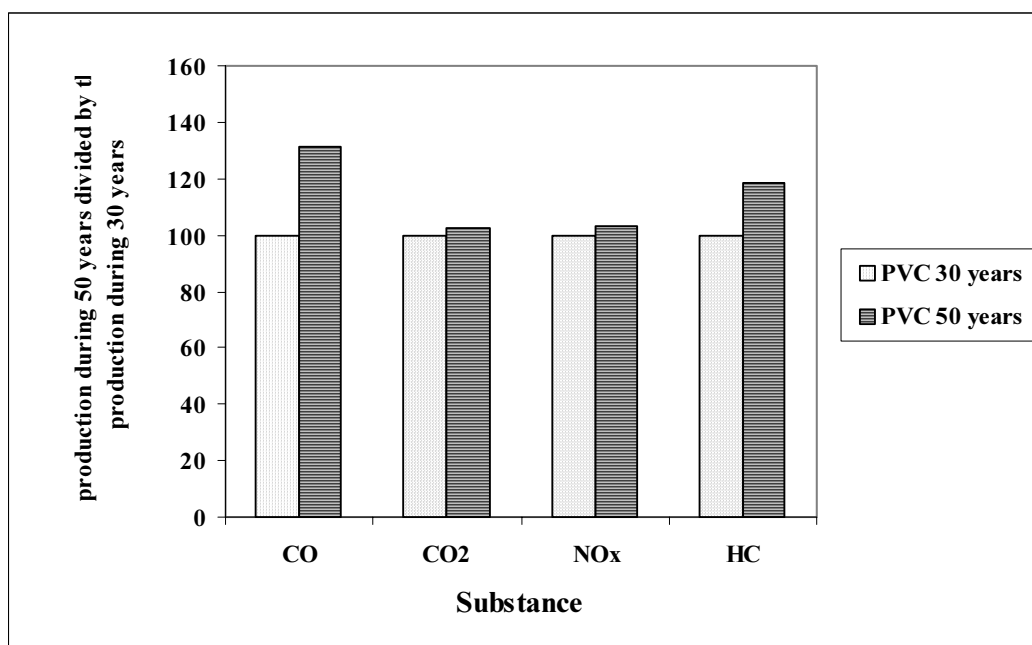


Figure 24 Comparison between the production of CO, CO₂, NO_x and HC for PVC during a 30 or 50 year life-time.

Table 10 Absolute values for the species in the 30 and 50 year scenarios.

PVC	CO (kg)	CO ₂ (kg)	NO _x (kg)	HC (kg)
30 years	8,93E+05	4,73E+08	1,41E+06	1,8E+05
50 years	1,17E+06	4,86E+08	1,45E+06	2,1E+05
Difference (%)	31,1	2,8	3,0	18,3

As seen in Figure 24, the only substance that is increased more than marginally when increasing the lifetime of the cable is CO. These results were expected, as the only gas of these four that is affected to any great degree when varying the amount of fires occurring

is CO (as seen in the next section in the comparison between the results of the model with and without fires).

The number of fires is increased in the model, thus the amount of CO produced in fires is increased. The CO production from fires is increased by 67%, making fires responsible for more than half the emissions of CO (53% in the 50 years scenario, compared to 41% in the 30 years scenario). The CO produced from production of “replacement” products (not cable) is also increased with 67%, which is explained by its proportionality to the number of fires occurring in the model.

The increase of CO₂ is only 3%. Most of this increase comes from “cable production”, but this increase is only 1,4% of the amount emitted during the 30 years scenario. The CO₂ produced from fires and production of replacements is increased with 67%, as expected.

No NO_x is produced in the fire modules (as it was not quantified in the fire experiments). Thus, the only emissions caused by fires come from the production of replacements of destroyed property. The increase of the emitted amount of NO_x is quite small, since the increase of fires destroying property (“Room fires” and “House fires”) is also quite small.

The increase in the production of HC is also marginal. The largest increase (in kg) in the production of HC comes from the production of “replacement products” (no cable), which is explained by the fact that the largest part of the total amount of HC’s produced from fires comes from this part.

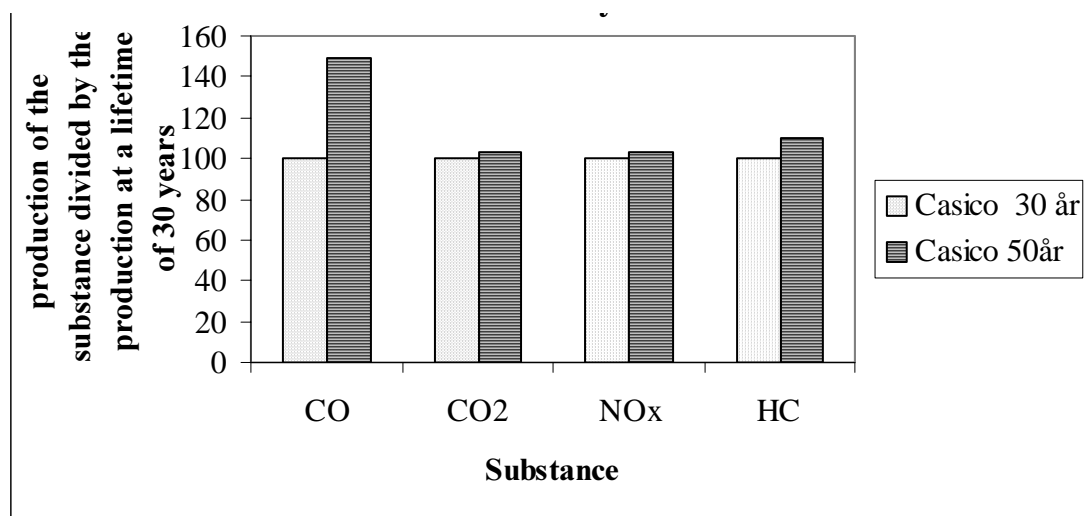


Figure 25 Comparison between the production of CO, CO₂, NO_x, and HC for CASICO during a 30 or 50 year life-time.

Table 11 Absolute values for the species in the 30 and 50 year scenarios.

CASICO	CO (kg)	CO ₂ (kg)	NO _x (kg)	HC (kg)
30 years	5,7E+05	4,7E+08	1,4E+06	3,5E+05
50 years	8,4E+05	4,8E+08	1,4E+06	3,8E+05
Difference (%)	48,9	2,9	3,0	10,1

As seen in Figure 25 and Table 11, the largest difference is found in the production of CO. The increase of CO₂, NO_x and HC are only marginal, with a possible exception in the case of HC. These results are similar to those found for the PVC cable and were predicted, as the only gases that are affected in any degree by the amount of fires are CO and HC (as seen in the next section in the comparison between the results of the model with and without fires).

The increase of CO is approximately 49%. The fire part of the model is responsible for 76% of the CO released during the life cycle. When increasing the lifetime of the cable, the production of CO from fires increased from 68% to 76% of the total amount produced. Thus, fires are very important when considering the production of CO during the life cycle of this cable.

The increase in the production of CO₂ is small, only 3%. The largest part of the increase comes from the production of the cables. This is, however, only an increase of 1,4% if compared with the production at a 30 years scenario. The production of CO₂ from fires and the replacement products (not cables) was increased with 67%, as expected.

The production of NO_x only increased with 3%, with the largest increase occurring in the production of replacements (not cable). Recall that no increase can be supported for the fire modules as NO_x emissions in the fire tests were below the level of quantification of our analysis instruments.

The production of HC increases with 10%. The largest part of the increase (in kg) comes from the production of replacements (not cable).

5.4 Results with and without fires

To investigate whether fires are important for the results of the LCA study, the number of fires used in the model was varied. In this section two cases are presented (with and without fires), with the four gases discussed in the previous section are presented in detail. These gases were chosen due to their importance as products from fires. The scenario that was used was Scenario 1, i.e. 100% of the cables were placed in landfills at their end of life with the exception of the amount of cables destroyed in fires.

As seen in Figure 26a, fires are very important for the results of the amount of CO produced during the life cycle of the two cables. Fires are responsible for about 50% of the production of CO from the PVC cable and about 70% from the CASICO cable in the scenarios where fires are included in the model. The CO produced due to fires is, however, not only produced in fires, but also during the production of replacements of the material that was destroyed in the fires. The production of replacement products is, however, only responsible for about 3% (7% of total amount of CO emissions caused by fires) of the total amount of CO produced from the PVC cable, and about 5% for the CASICO cable (7% of total amount of CO emissions caused by fires). In the emissions from fires, “secondary fires” are dominant.

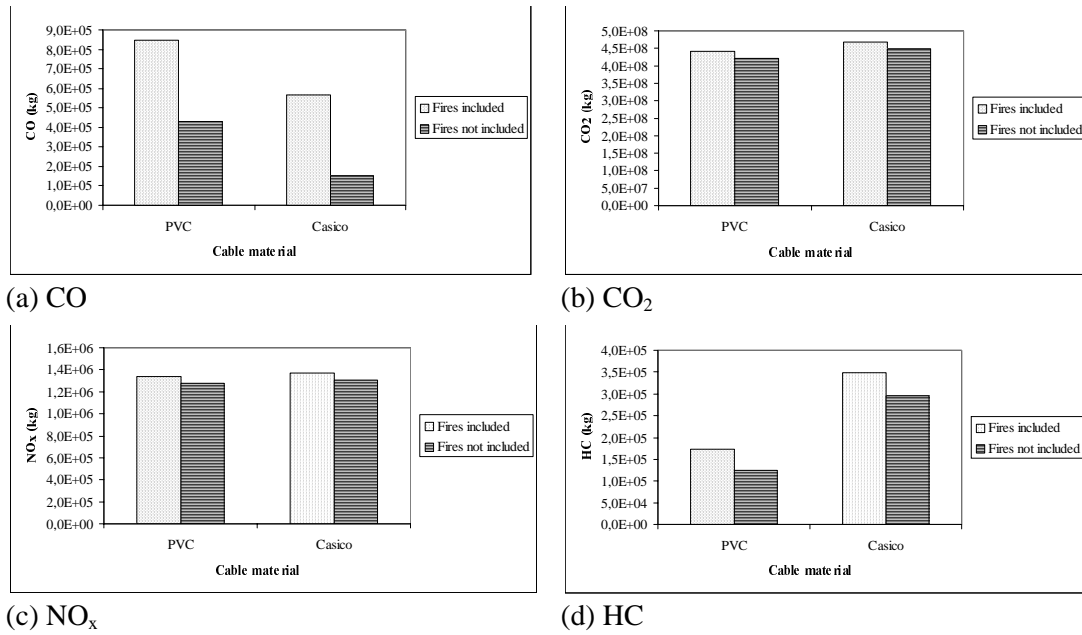


Figure 26 Comparison between species produced with and without fires in the LCA model for PVC and CASICO, 30 year lifetime.

As seen in Figure 26b, the emissions of CO₂ from fires are, compared to the total amount produced, quite small. Only about 4% of the CO₂ originate from fires in both cases. The production of replacements causes about 68% of the emissions of CO₂ produced due to fires for the PVC cable, and about 65% of the CO₂ from the CASICO cable. Thus, fires in themselves are not a major source of emissions of CO₂, since the production of the replacements are responsible for about 2/3 of the emissions of CO₂ caused by fires.

As seen in Figure 26c, the amount of NO_x emitted from fires, according to the calculations, are quite small. Fires cause only about 5% of the emissions of NO_x. As no emissions from fires specifically are calculated in the model, these numbers only contain the emissions of NO_x from the production of replacements.

As seen in Figure 26d, the difference between the emissions of HCs produced during the two scenarios (fires included, fires not included) can be considered to be important. In the case of PVC, the difference between the two scenarios is 28%, which is a significant difference. Considering the CASICO cable, the difference between the scenarios is 15%. Approximately 40% of the HCs produced in fires from both cables are actual fire emissions while the remaining part is produced during the production of replacements.

5.5 Importance of Secondary Fires

To investigate how the results of the scenarios investigated in the LCA are affected by the amount of secondary fires occurring, the amount of secondary fires has been varied from 10% to 100% of the worst case scenario defined in chapter 3, i.e., of 4.2% of the total length of cable used in the model.

The result of the LCA where 100% of the estimated amounts of secondary fires have been divided by those with 10% of the estimated amounts of secondary fires and presented in Figure 27 to Figure 30. If the result of this procedure is a number very close to 1, then the secondary fires have little effect on the total result of the LCA. If the number is larger than 1, however, the secondary fires are significant.

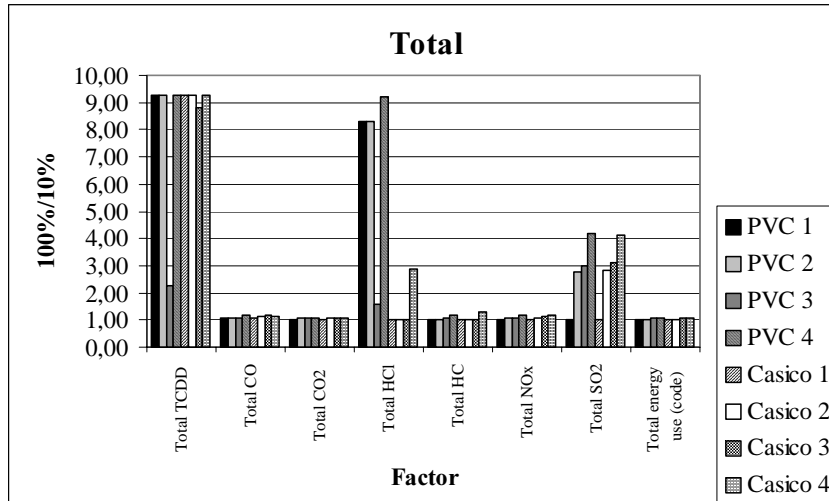


Figure 27 Relative importance of secondary fires on total emissions of species studied.

As seen in Figure 27, the substances that are affected most when the number of secondary fires is changed are TCDD, HCl and SO₂. These will be considered in more detail below. In each case, the effect is presented for both the total emission and the emission from the "fire", "cable production" and "incineration" categories in the model. The "fire" category does not include emissions from the production of replacement material for cables. This is included under "cable production".

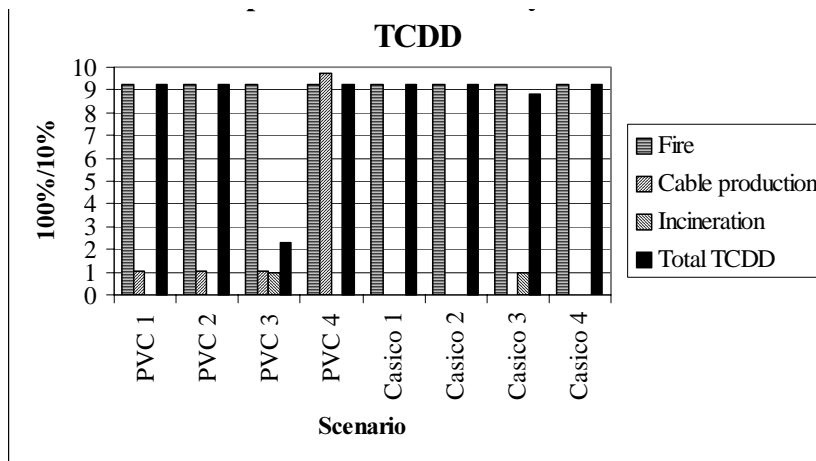


Figure 28 Relative importance of secondary fires on TCDD-equivalent production for all four scenarios for PVC and CASICO cable.

In the case of TCDD-equivalents the results are affected for both the cables in all scenarios. As seen in Figure 28, the part that is most important in the investigated scenarios is fire. The other parts (Cable production and Incineration) are not affected with the exception of Scenario 4 for PVC where cable production is significantly effected by the magnitude of the secondary fires. This is due to the fact when a large amount of cables are burned in fires a large amount of cables must be manufactured to replace the material involved in fires. The importance of production of replacement material is greatest for scenario 4 as a large portion of the polymer material for production of the original cables is presumed to come from recycled polymer material. In the case of the cables involved in fires

virgin polymer material needs to be produced by the model. The effect is not as great for the CASICO cable as it does not produce as much TCDD-equivalent in the polymer production as does the PVC.

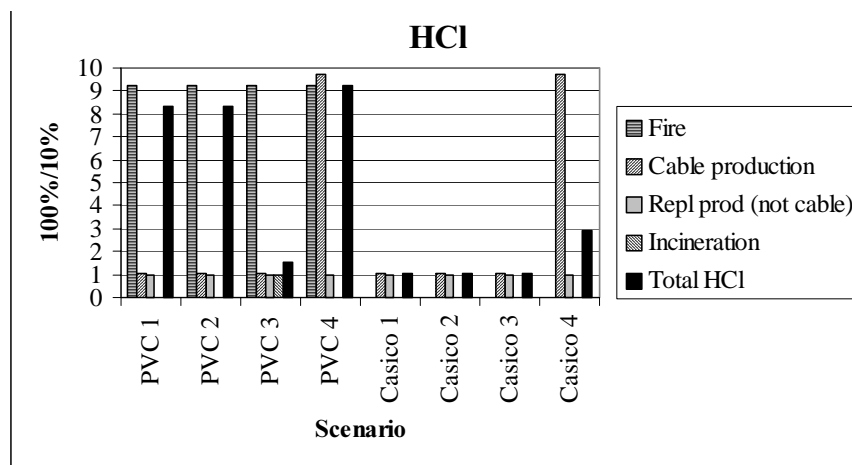


Figure 29 Relative importance of secondary fires on HCl production for all four scenarios for PVC and CASICO cable.

The emission of HCl for the PVC cable is significantly effected by our choice of secondary fire level in all scenarios. In the case of the CASICO cable only Scenario 4, where thermoplastic recycling is included in the model, is affected to any significant degree. This is illustrated in Figure 29.

The increase in HCl from the cable production in scenario 4 for the PVC cable is as explained for TCDD-equivalents above. The increase of HCl in Scenario 4 of the CASICO cable is due to the increased importance of the HCl production from the Cable production. In Scenario 4, where thermoplastic recycling is included in the model, the production of new cable material is decreased, thus decreasing the emissions of HCl, which comes from the production of EBA (the main polymer of the CASICO cable). As in the case of the PVC cable, the CASICO cables that are destroyed in secondary fires must be replaced by virgin material, and thus the production of HCl from the Cable production is significantly affected by the amounts of secondary fires occurring. In Scenario 4, where the Cable production of new cable material is low (about 4% compared to Scenario 1), the importance of the HCl emitted from the production of cables replacing the destroyed cables is very high. In fact, all the new material that is produced is made due to fires.

For the SO₂, see Figure 30, the importance of secondary fires is not significant at all in Scenario 1, where the ratio is very close to 1. This is due to the fact that the dominant source of SO₂ in scenario 1 is the production of copper, which is not significantly effected by the number of secondary fires. In the other scenarios, where copper recycling is included in the model, the importance of the emissions from fires increases for each scenario. As the importance of the emissions of SO₂ from fires increases, the importance of the secondary fires also increases. In the case of the CASICO cable, another important source of SO₂ is from Cable Production. This is most significant for scenario 4 for the same reasons detailed above for HCl although in this case related to the production of copper.

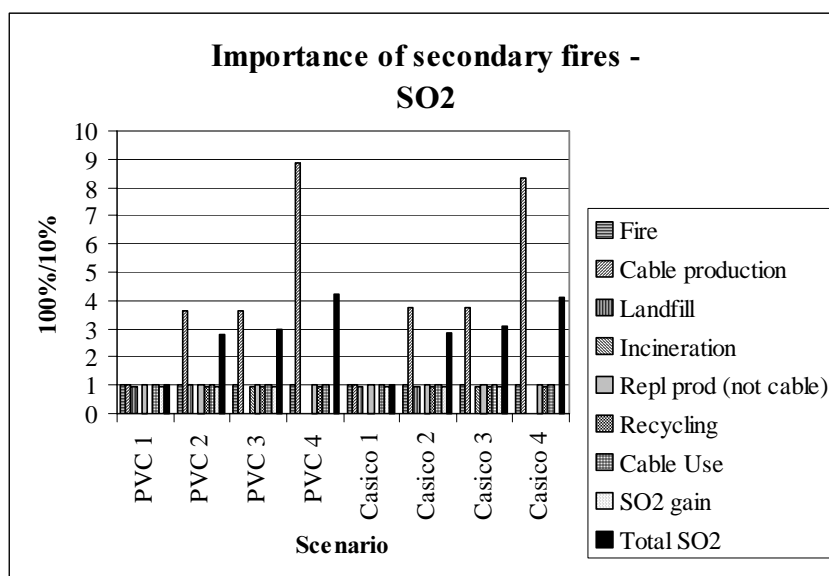


Figure 30 Relative importance of secondary fires on SO₂ production for all four scenarios for PVC and CASICO cable.

As discussed above, TCDD, HCl and SO₂ are the substances that are affected most by the amounts of secondary fires, when looking at the Total amount of the substance that is produced. If, however, all substances are examined in detail, it can be seen that the importance of the secondary fires increases for all species in Scenario 4. The increase in the Cable production is the reason for this. Thus, it can be concluded that the amount of secondary fires is of greatest importance in Scenario 4, where recycling of the cable materials is at its highest level. This is corroborated if the use of energy is examined, it can be seen that the only Scenario that is affected is Scenario 4, and that the only energy resources used in this scenario that are affected by an increase in the secondary fires are those used during the cable production.

In summary, the most important change when the numbers of secondary fires are changed is the change that occurs in Scenario 4, although some effects are seen for TCDD, HCl and SO₂ in the other scenarios. The explanation for this is the decreased production of cable material in Scenario 4, which is due to the increased recycling of cable material. If 100% of the estimated amounts of secondary fires occur, a large amount of cables must be replaced, resulting in a large production of emissions from the Cable production category. If, however, 10% of the estimated amounts of secondary fires occur, the production of emissions from the cable production stage of the life cycle is much smaller with relatively smaller emissions.

5.6 Uncertainty Analysis

As one of the final stages of the LCA work, an uncertainty analysis of the results of the LCA has been performed. This was done in order to investigate the reliability of the results, and how sensitive the model is for small uncertainties or changes in the input used in the model.

Normally, the input data used in a LCA is not absolutely accurate. Some uncertainty of the data used is involved. The effect of this uncertainty can be studied and analysed, to estimate the reliability of the results of the total system.

5.6.1 Method of Analysis

The uncertainty analysis was performed using the specific uncertainty analysis function of the KCL-ECO software. In the software, it is possible to choose the specific substance of interest and the level of uncertainty that is considered to be appropriate for the substance.

The parameter equations used in the LCA software are of the form:

$$Variable_1 = factor \times Variable_2.$$

The factor used in each equation in the uncertainty analysis is a specific uncertainty percentage. Different levels of uncertainty can be used for different equations, and it is also possible to specifically choose which equations to study. When the specific substance (or equation) and the uncertainty percentage for each substance (or equation) have been chosen, the uncertainty analysis can be performed.

During the uncertainty analysis, the software chooses a random value of the factor. This factor lies between the specified uncertainty limits that have been chosen for each equation. This procedure is performed for all equations selected, and is repeated a number of times (generally between 100 and 8000 times, the amount of cycles being specified before the uncertainty analysis is started).

The results are presented as a 95% confidence interval, where the starting value, the calculated mean value and the 95% min and max values are presented, and the results of all the calculations made during the uncertainty analysis are presented as a frequency distribution. The 95% min and max values are the amount of the substance where 95% of the results of the uncertainty analysis are either above this result (95% min) or below it (95% max). The standard deviation of the results is also calculated.

The results can be considered to show how stabile the model is against small “disturbances” or uncertainties in the input used during the calculation of the total system. If the 95% min and max values are approximately the same as the chosen uncertainty percentage, and the starting value and the calculated mean value are the same or very close to each other, then the model can be considered to be stabile and rather insensitive to small changes or uncertainties.

The substances that were selected for more detailed study were CO₂, NO_x, SO₂, HC and TCDD. The levels of uncertainty chosen for these substances are given in Table 12. The scenario that was used during the uncertainty analysis for both the cables was Scenario 1, i.e. all cable material (copper and plastics) to landfill.

Table 12 Uncertainty percentages used in the uncertainty analysis.

Substance	Uncertainty
CO ₂	± 5%
NO _x	± 10%
SO ₂	± 10%
HC	± 30%
TCDD	± 30%

Different species can be considered to have different uncertainties. Regarding the calculation of CO₂, for instance, the factors used in the equations can be considered to be quite certain, and therefore the percentage that was used was only 5%. The factors describing the production of TCDD, however, can be considered to have a larger uncertainty than the factors for the production of CO₂. Thus, the uncertainty percentage used for TCDD is larger than the percentage used for the production of CO₂.

It should be stated that the results of the uncertainty analysis could be dependent on the uncertainty percentage used in the analysis. The calculated sample mean value should be approximately the same as the starting value, independent of the percentage used if the model is stable, but the width of the confidence interval and the standard deviation may vary with the estimated uncertainty percentage.

5.6.2 Results of Uncertainty Analysis

Carbon dioxide, CO₂:

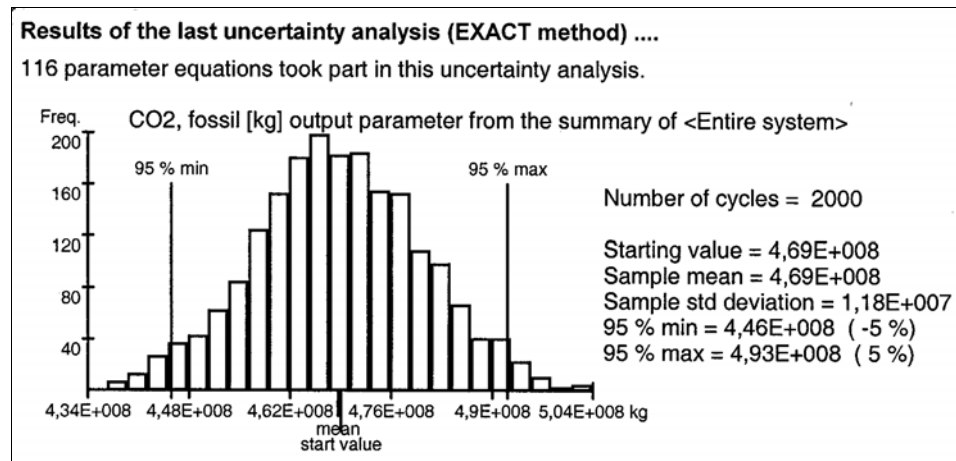


Figure 31 Results of the uncertainty analysis of CO₂ for the CASICO cable.

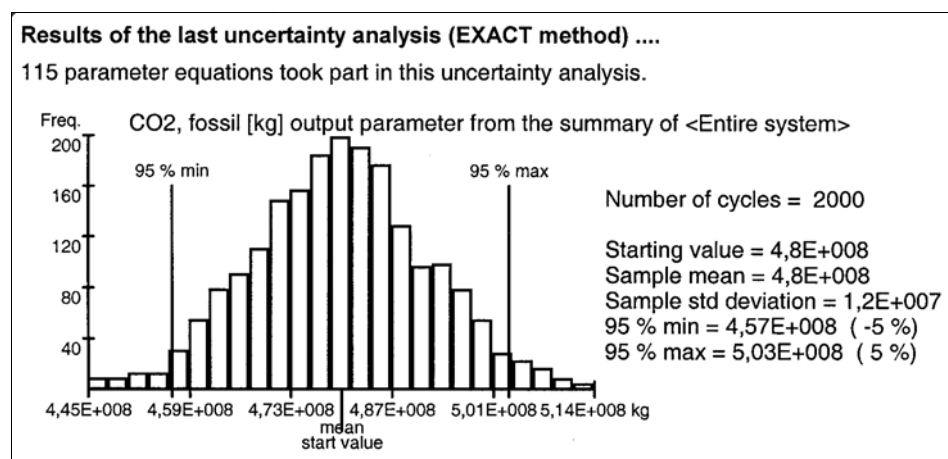


Figure 32 Results of the uncertainty analysis of CO₂ for the PVC cable.

As seen in Figure 31 and Figure 32, the starting value (the actual result of the LCA calculation) and the calculated sample mean values (the mean value calculated during the uncertainty analysis) are exactly the same for both the cables. The calculated 95% min and max values are the same as the uncertainty used in the analysis. Thus, the part of the

model describing the production of CO₂ can be considered to be stable and the result of the life cycle assessment to be quite reliable.

Nitrogen oxides, NO_x.

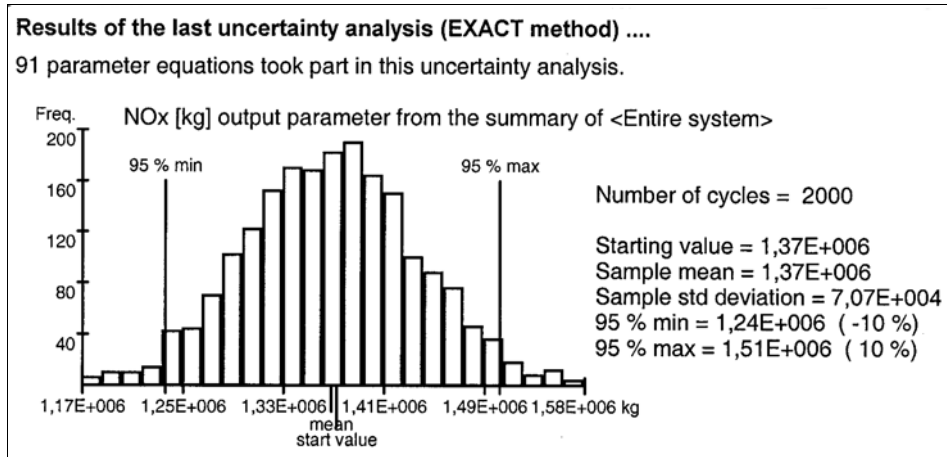


Figure 33 Results of the uncertainty analysis of NO_x for the CASICO cable.

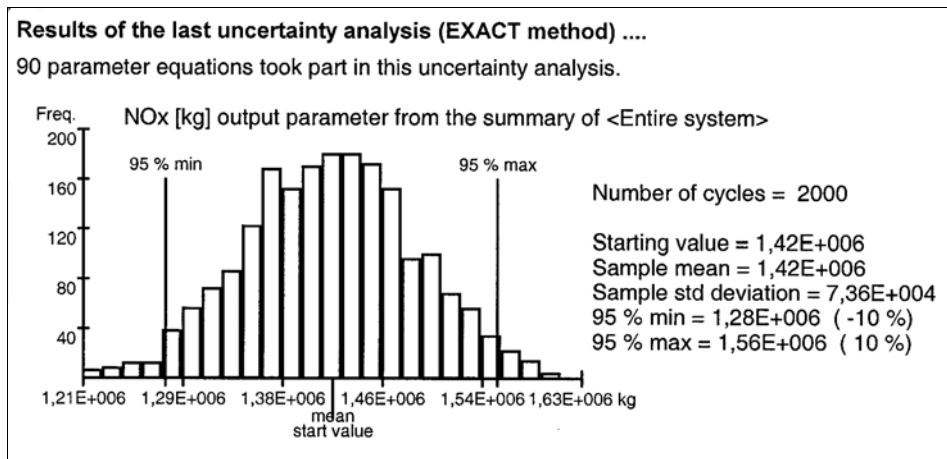


Figure 34 Results of the uncertainty analysis of NO_x for the PVC cable.

As seen in the results of the uncertainty analysis of NO_x, Figure 33 and Figure 34, the starting value and the calculated sample mean values are exactly the same for both the cables. The calculated 95% min and max values are the same as the uncertainty used in the analysis, which means that 95% of the results above and 95% of the results below the calculated mean value is within the uncertainty percentage that was used for the NO_x equations during the uncertainty analysis.

Sulphur dioxide, SO₂:

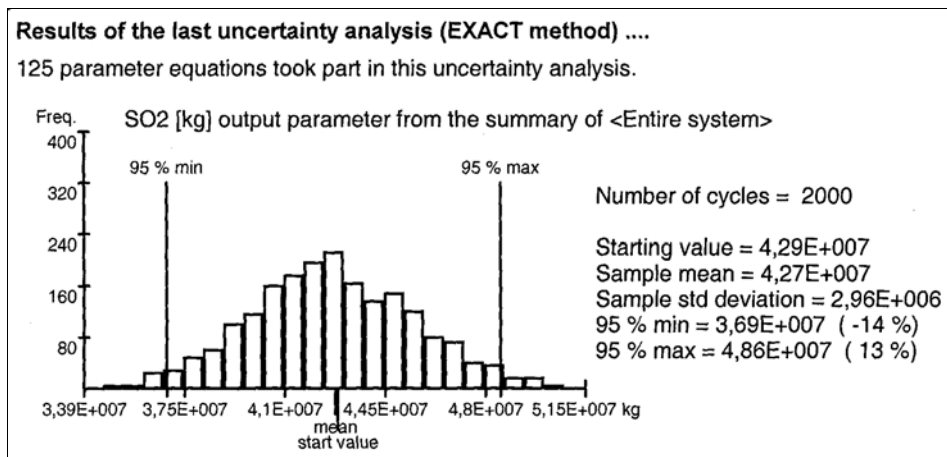


Figure 35 Results of the uncertainty analysis of SO₂ for the CASICO cable.

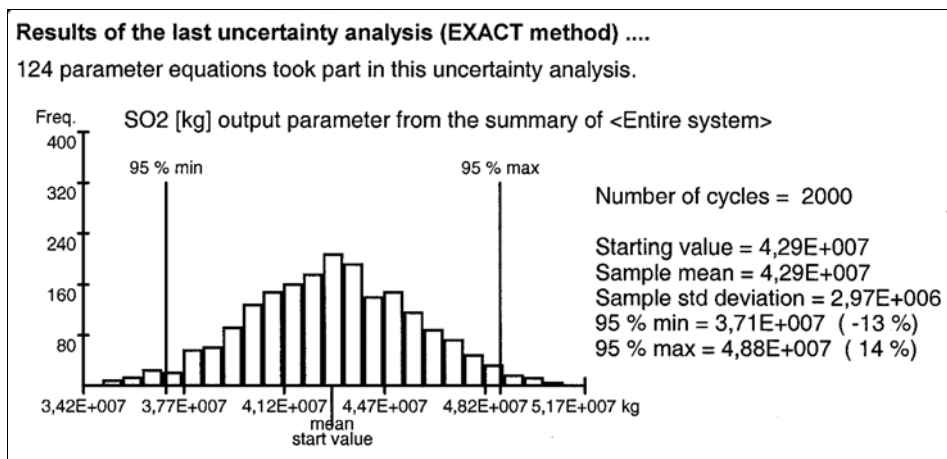


Figure 36 Results of the uncertainty analysis of SO₂ for the PVC cable.

The starting value and the sample mean value are the same for the PVC cable and almost the same for the CASICO cable (0,5% difference between the starting value and the sample mean) as shown in Figure 35 and Figure 36. The 95% min and max values (in %) are slightly larger than the uncertainty percentage used in the analysis. Thus, the equations used to describe the production of SO₂ can be considered to be more sensitive to disturbances and uncertainties than for the gases discussed previously. However, as stated previously, the sample mean is similar to the starting value, implying that the model can be considered quite stable.

Hydrocarbons, HC:

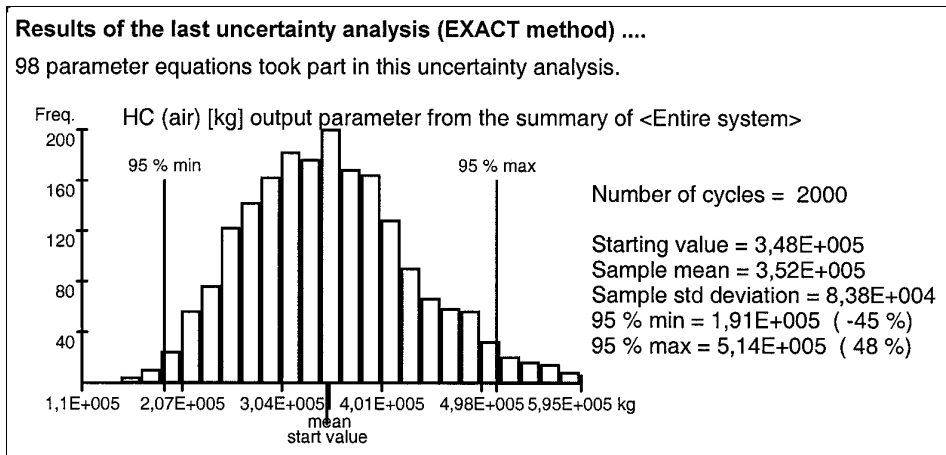


Figure 37 Results of the uncertainty analysis of HC for the CASICO cable.

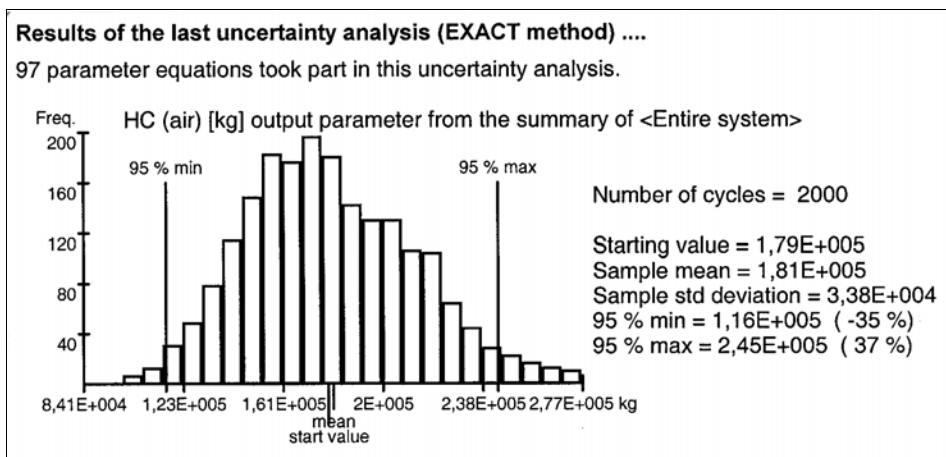


Figure 38 Results of the uncertainty analysis of HC for the PVC cable.

The sample mean value and the starting value differ about 1% for both the cables as shown in Figure 37 and Figure 38. The difference between the results and the uncertainty percentage used are quite large. The percentage used was $\pm 30\%$, and the 95% min and max values are approximately 45% for the CASICO cable and approximately 36% for the PVC cable. Thus, there is a difference between the results of the two cables, and the uncertainty is larger for the CASICO cable than for the PVC cable.

Tetrachlorodibenzodioxin equivalents, TCDD:

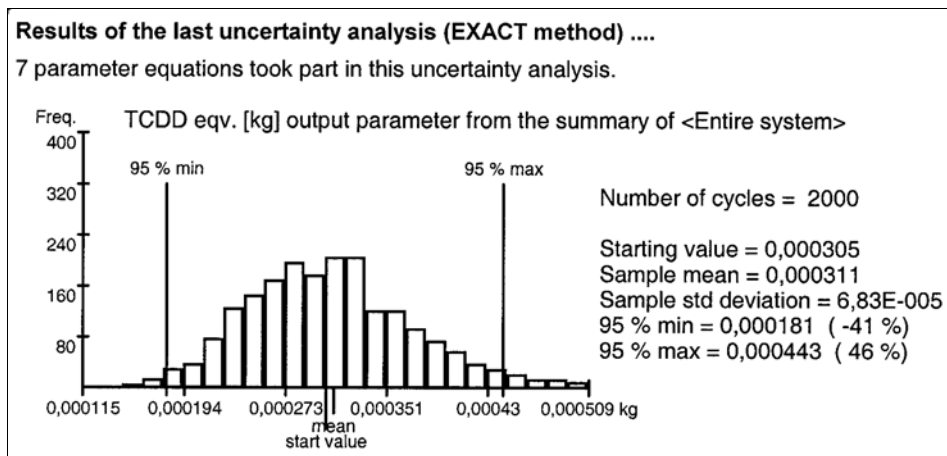


Figure 39 Results of the uncertainty analysis of TCDD for the CASICO cable.

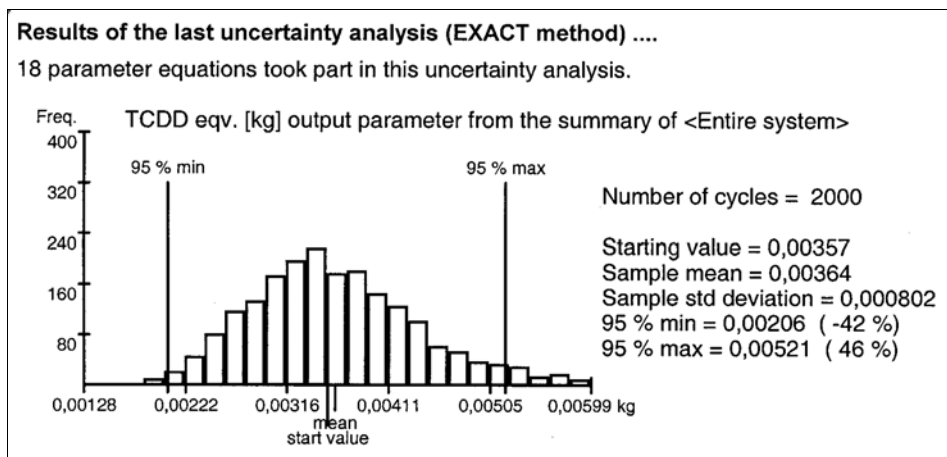


Figure 40 Results of the uncertainty analysis of TCDD for the PVC cable.

The uncertainty analysis on TCDD resulted in a small difference between the starting value and the sample mean, approximately 2% for both cables as shown in Figure 39 and Figure 40. The 95% min and max values, however, differ when compared to the uncertainty percentage used in the analysis. The percentage used was 30%, which resulted in 95% min and max values of approximately 45% for both the cables, which is 50% larger than the percentage used. This may indicate that the part of the model that describes the production of TCDD can be sensitive for changes, which may result in a rather large uncertainty regarding the result of the dioxins produced during the life cycle of the cables described in the LCA model.

5.6.3 Conclusions of Uncertainty Analysis

As seen in the results presented above, the results of the two cables are quite similar. The frequency distributions presented in the confidence intervals have the same shape as Gaussian curves, and the results of the uncertainty analysis are similar in most of the cases. The only substance where the results of the uncertainty analysis can be considered to differ between the two cables is hydrocarbons (HC), where the 95% min and max range are larger for the CASICO cable than for the PVC cable.

For CO₂, SO₂ and NO_x, the 95% min and max values were of the same size as the estimated uncertainty percentage. This indicates that the results of these substances are reliable and stable against uncertainties.

Regarding HC and TCDD, the uncertainty analysis indicates that these substances have a higher uncertainty than CO₂, SO₂ and NO_x. However, this can be said to be in agreement with the results of the LCA, as the total production of HC and TCDD are more dependent on the production from fires than the other gases. The specific production of a fire gas is very dependent on the conditions that prevail in the fire. The production of gases from the fires experiments that were performed for this report shows the production under the conditions during those tests. The production of the same gases can be different if the tests are performed again, as the conditions prevailing during the fire tests can be different. Thus, the production of a specific fire gas can be difficult to specify, and thus the uncertainty also is larger for fire gases than for gases produced under controlled conditions.

5.7 References

- 1 Dinelli, G., Viti, N., Miola, G., Fara, A., de Nigris, M., Gagliardi, E., End-of-Life Management of Power Distribution Cables: Improvement Options Derived from an Analytical Approach, MEIE '96, Versaille, 1996.
- 2 de Nigris, M., Use of LCA Approach to Evaluate the Environmental Impact of Distribution Transformers and Implementation of Improvement Options, MEIE 2000, Paris, 2000.

6 Fire-LCA Model – Conclusions

A novel Life-Cycle Assessment (LCA) model has been defined for the investigation of the environmental impact of the choice of material in cable production. In one case polyolefin based material is used while in the other case PVC material is used. In both cases equivalent fire behaviour is assumed and a fire model is established based on existing fire statistics. This study represents the second full application of the Fire-LCA model.

The energy use of the model and a large number of emission species have been presented in the results of the Fire-LCA model for Cables. These species include CO, CO₂, unburned hydrocarbon (HC), NO_x, SO₂, TCDD-equivalents, and HCl. For most species, one sees a decrease in emissions for each scenario from scenario 1 to scenario 4 with the exception of scenario 3. In scenario 3 one assumes energy recycling of the plastic material, which leads to, increased emissions from the incineration part of the model. The effect of this is most marked for those species with very low emission from other sources such as TCDD-equivalents and HCl. In these cases the treatment of allocation of TCDD and HCl emissions from incineration to the chlorine content in the waste leads to a significant increase of these emissions in scenario 3. Similarly, a significant increase is seen in the emissions of CO and CO₂ as these species are produced in large quantities from incineration.

When considering the gases that have been discussed above TCDD-equivalents, HCl, CO and HC were found to be influenced significantly by the incorporation of fires in the LCA model.

If the production of CO from fires were to be omitted, a large amount of CO would be left unnoticed, resulting in a large error in the results of the study. The main reason for CO being so important is that most of the fires where cables are destroyed are vitiated fires. In the beginning of the fire scenario, the fire may be well ventilated, but as the fire continues the oxygen concentration in the area where the cables are mounted decreases and the atmosphere becomes vitiated. Thus, the fires used in the model are considered to be vitiated.

The production of HC increased by about 28% when the emissions from fires and from other parts originating from the occurrence of fires were added to the result. In the case of CO fires in itself was responsible for the main part of the emissions, but in the case of HC the production of replacements of destroyed property caused about 60% of the emissions. That part, however, is caused by the fire and should therefore be added to emissions caused by fires.

Similarly input information for both TCDD-equivalents and HCl was available mainly from the fire tests and through estimates of emissions from incineration. Little information was available concerning the emission of these species from other sources in the model.

In contrast, CO₂ and NO_x were not affected in any greater way. Fires caused only about 5% of the total emissions of the two gases, which probably is in the region of the uncertainty of the model.

The influence of the choice of exact life time for the cable was not found to be important in determining the general conclusions in the model and it is suggested that a 30 year life time (in agreement with literature data) is a reasonable choice.

An uncertainty analysis has also been performed to ensure that the conclusions are not prone to large uncertainty. The results of this analysis show that the model is stable and the species presented in detail are not affected to any great degree by changes in key parameters. This implies that the model is robust and the conclusions sound.

The results of this comparison indicate that the Fire-LCA model is able include the impact of fire emissions on the overall life cycle of two products with equivalent fire performance and not just (as in the previous study) products of differing fire performance. It is, however, noted that the model is perhaps most useful when comparing products with differing fire performance.

6.1 Future Work

The Fire-LCA model is still under development and efforts are underway to expand the scope of the risk analysis to include such aspects as acute and chronic toxicity and the economic cost-benefit of various alternatives.

The model in its present design is, however, being applied to a comparison of the environmental impact of two pieces of furniture with different fire performance (one corresponding to the UK regulations and the other to typical continental regulations). It is expected that this work will be published in 2002.

Appendix 1 Photographs

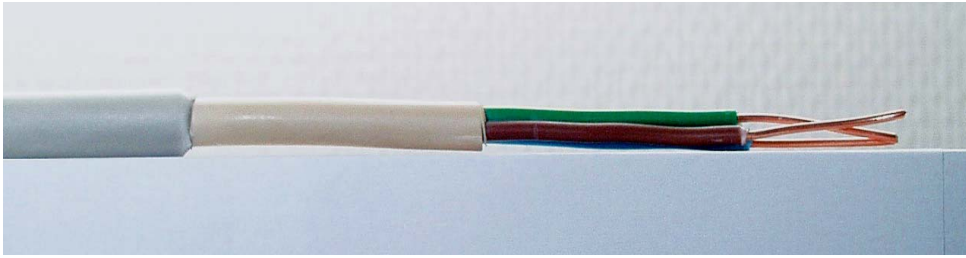


Figure 41 CASICO cable.

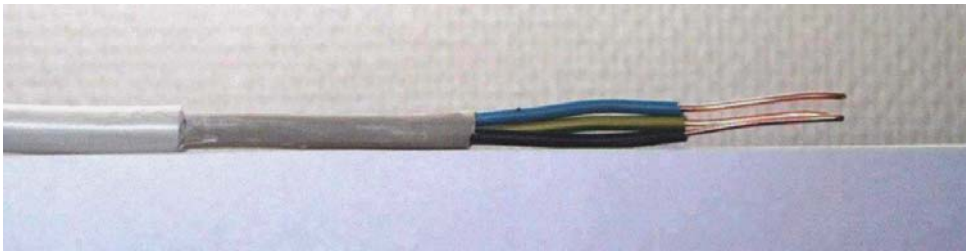


Figure 42 PVC cable.



Figure 43 Photo showing the typical mounting procedure used for all the IEC 332-3 tests.



Figure 44 Photo of unburned cables at the base of cable tray. This example was taken after the well-ventilated CASICO experiment.



Figure 45 Remains of PVC cable after typical experiment. Note that the CASICO cable had the same appearance after the experiments.

Appendix 2 Results of DIN 53436 tube furnace experiments

A.1 Results – PVC

At first, whether the fire performance of the sample was dependent on the colour of the material present in the insulation material was investigated. Therefore, tests on three samples of each cable were conducted at 650°C with 100 mg sample/l air. The samples consisted of 1/3 of the cable sheath and one of the three insulated wires. Thus, one test was performed on every insulated wire that was in the cable at 650°C with 100 mg sample/l air. Since no major difference could be found between the fire performance of the samples investigated, only one test was performed on each cable on the other temperatures and ventilation ratios chosen. Further, only one set of experiments are presented for each cable at 650°C with 100 mg sample/l air.

The only compounds that were quantified with the FTIR analysis equipment were CO₂, CO and HCl during all the experiments with the PVC cable.

650°C, 100 mg/l air

The sample smouldered during the experiment, producing a thin smoke and relatively low amounts of CO₂. Flaming combustion only appeared during a short period of time at the end of the experiment, resulting in a thick black smoke, and an increased production of CO₂. The results of the quantification using the FTIR are summarised in Table 13. The time resolved concentration profiles are summarised in Figure 46.

Table 13 Compounds detected and quantified by FTIR at 650 °C 100 mg/l air, black insulation, PVC.

	CO ₂	CO	HCl
Weight combusted (g):	5.1		
Tot mass (g)	2.301	0.408	0.704
Yield (g/g combusted material):	0.453	0.080	0.139
Max g/s:	0.0057	0.0004	0.0006
Max concentration:	9.7%	10887 ppm	12792 ppm

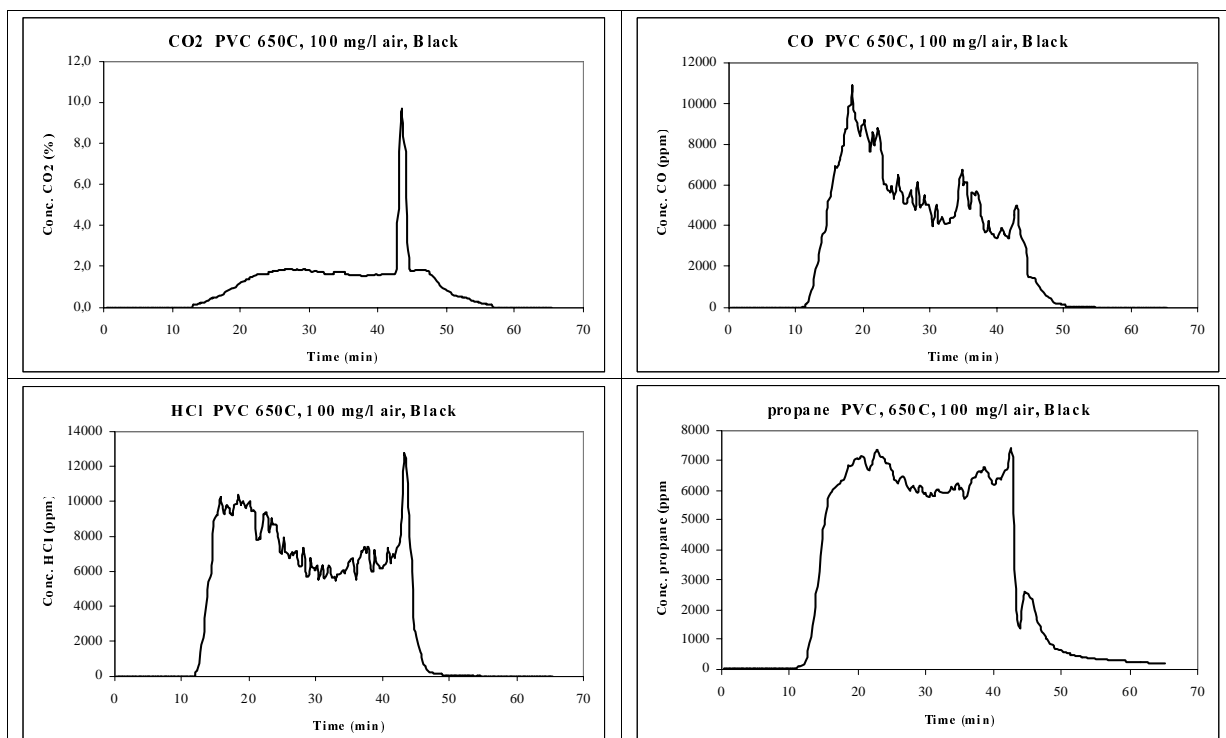


Figure 46 Compounds detected by FTIR and FID at 650 °C 100 mg/l air, black insulation, PVC.

The concentration of CO produced during the experiment was high, with its highest production at the start of the experiment and thereafter showing a steady decline during most of the time of the experiment. After about 45 minutes, when flaming combustion started, the production of CO decreased fast.

The production of HCl was very high at the start of the experiment, but started to decrease slowly. However, the production started to increase again after about 35 minutes, and reached its highest peak during the period of time when the sample was subjected to flaming combustion.

The production of non-combusted hydrocarbons detected by the FID was, as seen in Figure 46, quite constant until flaming combustion appeared. The detected concentration of hydrocarbons is related to “ppm propane”, and not the specific hydrocarbons that can be produced when the material is decomposed. The results provide useful information concerning the relative production of hydrocarbons in the different experiments. The results are summarised in Table 14.

Table 14 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 100 mg/l air, black insulation, PVC.

	Propane
Total mass (g)	0.535
Yield (g/g combusted material):	0.105
Max g/s:	0.0003
Max ppm propane:	7426

350°C, 100 mg/l air

No flaming combustion appeared at all; instead the sample bubbled, boiled and became dark when it reached the middle section of the oven. As seen in Table 15, the maximum concentration of CO₂ was 0,4%, and the yield was 0.094 g/g combusted material, which is about 1/5 of the yield produced during the experiments at 650°C. The weight combusted was 3.6 g, which is about 1.3 g lower than the experiments performed at 650°C. The time resolved concentration profiles for both the FTIR and FID analyses are summarised in Figure 47.

Table 15 Compounds detected and quantified by FTIR at 350 °C 100 mg/l air, PVC.

	CO ₂	CO	HCl
Weight combusted (g):	3.6		
Tot mass (g)	0.341	0.028	0.696
Yield (g/g combusted material):	0.094	0.008	0.193
Max g/s:	0.0002	0.0000	0.0006
Max concentration:	0.4%	920 ppm	11446 ppm

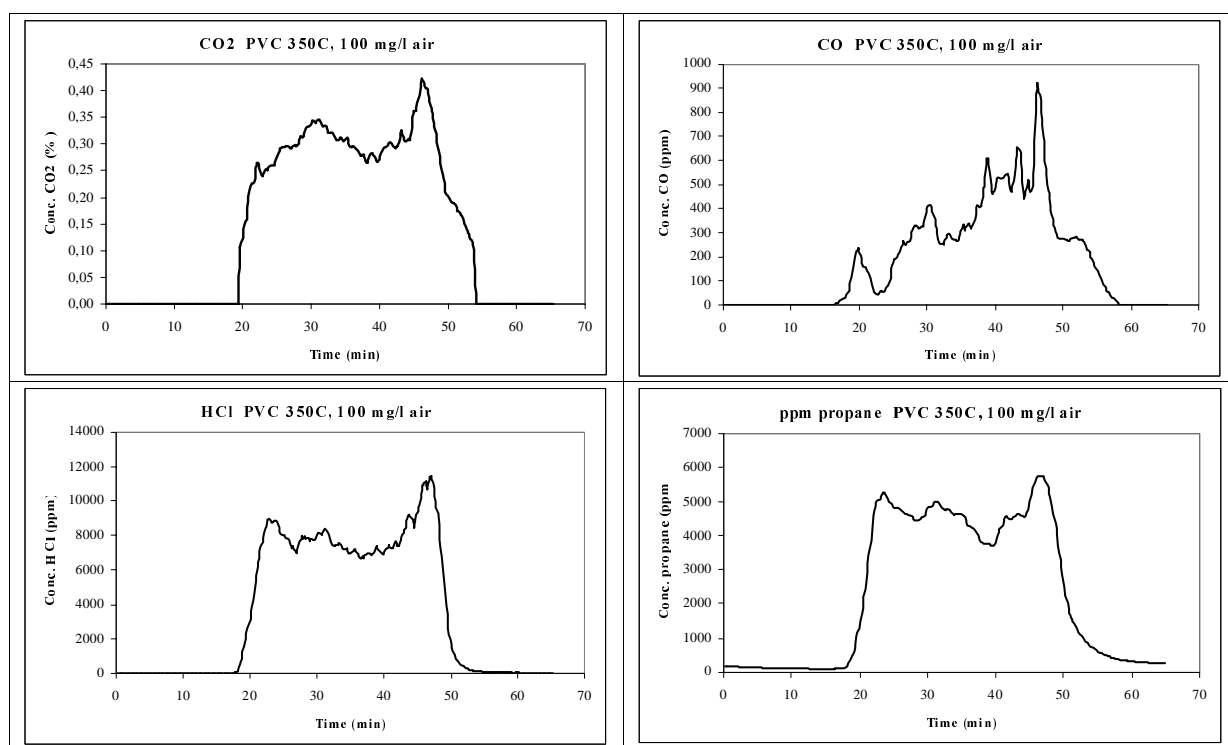


Figure 47 Compounds detected by FTIR and FID at 350 °C 100 mg/l air, PVC.

The production of CO was considerably lower at 350°C than at 650°C. The maximum concentration and the total mass produced of CO for the experiments at 650°C is more than 10 times higher than the results of this experiment.

The production of HCl seems not to differ so much if compared with the production at 650°C. The total production was about the same as the one at 650°C, but the highest concentration reached was lower. The weight combusted was lower compared to the experiments at 650°C, resulting in a higher yield at this experiment. Since no flaming combustion occurred, no sharp peaks in the production of HCl appeared.

The production of non-combusted hydrocarbons was quite constant during the experiment (see Figure 47). The maximum concentration was a little bit lower compared to the results obtained at 650°C, but the yield was about the same as the ones obtained from the experiments at 650°C. More non-combusted hydrocarbons were generated during this experiment compared to the ones performed at 650 °C. The full FID results are summarised in Table 16.

Table 16 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 100 mg/l air, PVC.

	Propane
Total mass (g)	0.386
Yield (g/g combusted material):	0.107
Max g/s:	0.0002
Max ppm propane:	5738

650°C, 400 mg/l air

No flaming combustion appeared at all, instead the sample bubbled and boiled and became dark when it passed the entrance of the oven. The weight combusted was the same as in the experiments performed under a normal atmospheric condition. The FTIR results are summarised in Table 17. The time resolved species profiles are summarised in Figure 48.

Table 17 Compounds detected and quantified by FTIR at 650 °C 400 mg/l air, PVC.

	CO₂	CO	HCl
Weight combusted (g):	5.0		
Total mass (g)	1.201	0.182	0.705
Yield (g/g combusted material):	0.243	0.037	0.142
Max g/s:	0.0007	0.0001	0.0005
Max concentration:	1.2%	3709 ppm	9864 ppm

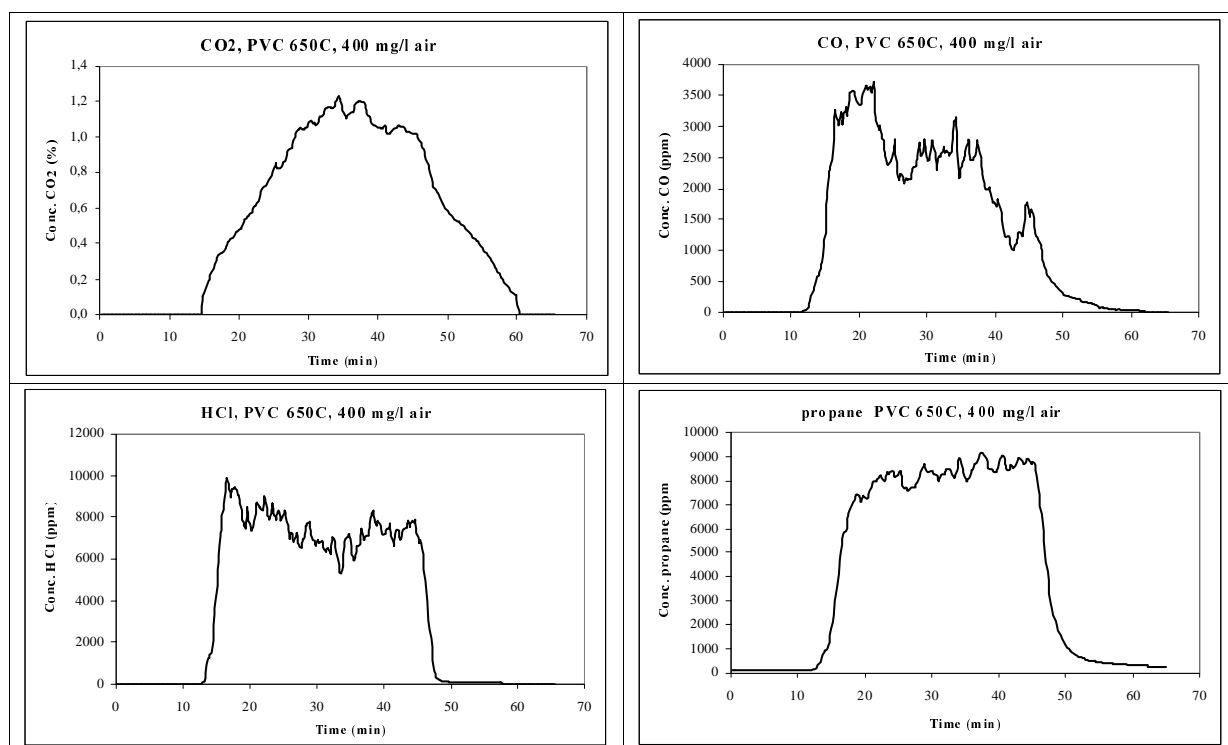


Figure 48 Compounds detected by FTIR and FID at 650 °C 400 mg/l air, PVC.

The production of CO was at its highest peak in the beginning of the experiment. After that, the production started to decrease slowly. The maximum concentration detected and the yield was about half the maximum concentration and yield produced at 650°C, 100 mg/l air.

The production of HCl was about the same as the other experiments mentioned above. The yield was about the same as the experiments at 650°C, 100 mg/l air.

The production of non-combusted hydrocarbons was constant at around 9000 ppm, and the maximum concentration detected was higher than the concentrations obtained at experiments discussed earlier. Compared with the experiments obtained at well-ventilated conditions, the yield was about 45% higher. The difference between the production of hydrocarbons during well-ventilated and vitiated conditions was not large. The FID profile is shown in Figure 48 and the results are summarised in Table 18.

Table 18 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 100 mg/l air, PVC.

	propane
Total mass (g)	0.705
Yield (g/g combusted material):	0.142
Max g/s:	0.0004
Max ppm propane:	9148

350°C, 400 mg/l air

No flaming combustion appeared at all, instead the sample bubbled and boiled, swelled and darkened in the middle of the oven. The FTIR results for this experiment were unreliable and have not been reported. However, the results from the analysis made by the FID can be compared with the results obtained at the other experiments. The FID profile is shown in Figure 49 and the average results are summarised in Table 19.

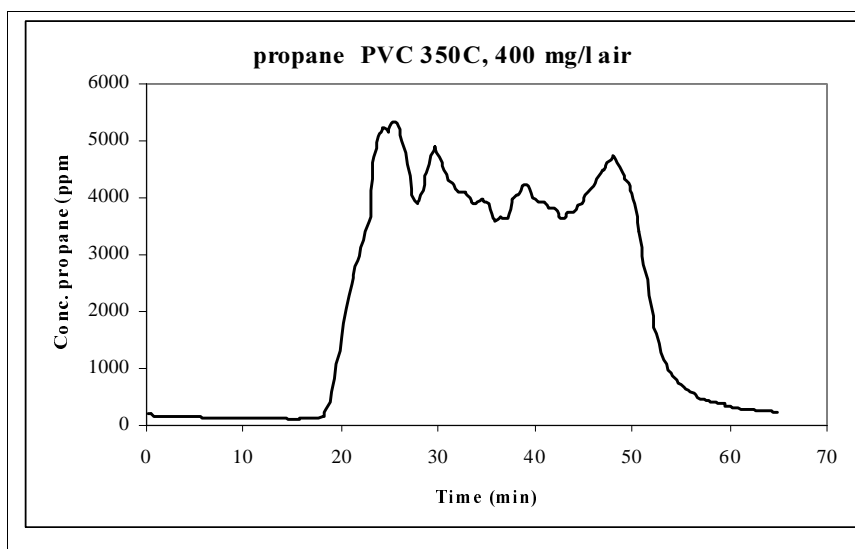


Figure 49 Compounds detected by FTIR and FID at 650 °C 400 mg/l air, PVC.

Table 19 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 100 mg/l air, PVC.

	propane
Total mass (g)	0.363
Yield (g/g combusted material):	0.097
Max g/s:	0.0002
Max ppm propane:	5339

Compared with the results from 350°C, 100 mg/l air, the total mass produced is a little bit lower. The weight combusted is a little bit higher, which results in a yield that is a little bit lower than the yield at 350°C, 100 mg/l air. The maximum concentration is a little bit lower than the maximum concentration obtained at 350°C, 100 mg/l air.

The yield at 650°C, 400 mg/l air is about 50% higher than the one obtained at 350°C, 400 mg/l air. This difference is larger (in percent) than the one between 350°C and 650°C at 100 mg/l air. This result is, however, not very surprising, since the produced amount of hydrocarbons is consumed in the combustion processes that appeared under well-ventilated conditions.

A.2 Results – CASICO

CO₂ and CO were the only compounds that were quantified with the FTIR analysis equipment during all the experiments with the CASICO cable.

650°C, 100 mg/l air

After the sample had ignited (after about 17 minutes), the sample burned continuously, with the exception of the period between 24 and 27 minutes, where the flame faded and disappeared. As seen in Figure 50, the flame size varied a lot. Since the sample burned so much, the production of CO₂ was quite high. The average values of the compounds detected using the FTIR are summarised in Table 20.

Table 20 Compounds detected and quantified by FTIR at 650 °C 100 mg/l air, brown insulation, CASICO.

	CO ₂	CO
Weight combusted (g):	4.9	
Tot mass (g)	8.455	0.359
Yield (g/g combusted material):	1.715	0.073
Max g/s:	0.0076	0.0009
Max concentration:	12.9%	23266 ppm

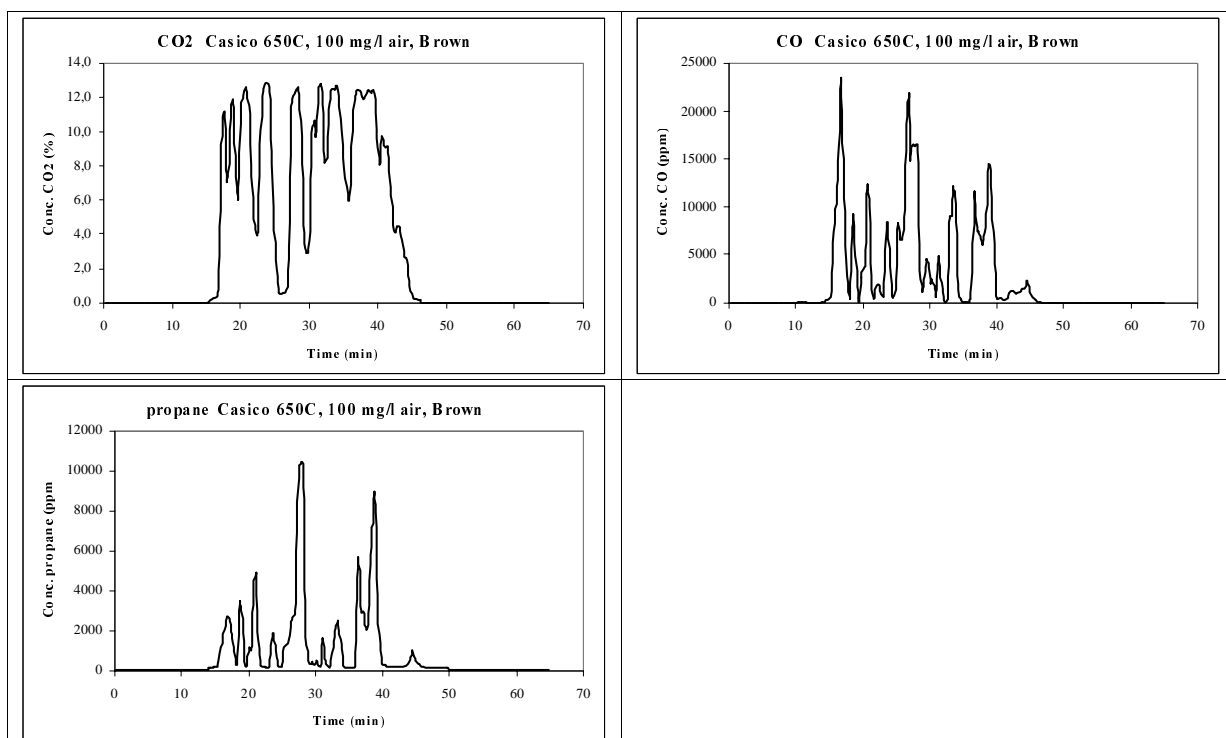


Figure 50 Compounds detected by FTIR and FID at 650 °C 100 mg/l air, brown insulation, CASICO.

The production of CO varied a lot during the experiment, with large peaks at the beginning before flaming combustion started and when the flame size decreased or the fire seized.

The production of non-combusted hydrocarbons also varied a lot, due to the varying behaviour of the flame. The largest production of hydrocarbons was detected approximately at the first time the flame. When flaming combustion started anew, the production of hydrocarbons decreased fast. The average FID results are summarised in Table 21.

Table 21 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 100 mg/l air, black insulation, CASICO.

	propane
Weight combusted (g):	4.9
Total mass (g)	0.141
Yield (g/g combusted material):	0.029
Max g/s:	0.0005
Max ppm propane:	10840

350°C, 100 mg/l air

No flaming combustion appeared during the experiment; instead the sample darkened, shrank and swelled. The average results from the FTIR analysis are summarised in Table 22 and the species profiles are shown in Figure 51.

Table 22 Compounds detected and quantified by FTIR at 350 °C 100 mg/l air, CASICO.

	CO₂	CO
Weight combusted. (g):	0.3	
Total mass (g)	0.126	0.043
Yield (g/g combusted material):	0.436	0.148
Max g/s:	0.0001	0.0000
Max concentration:	0.1%	820 ppm

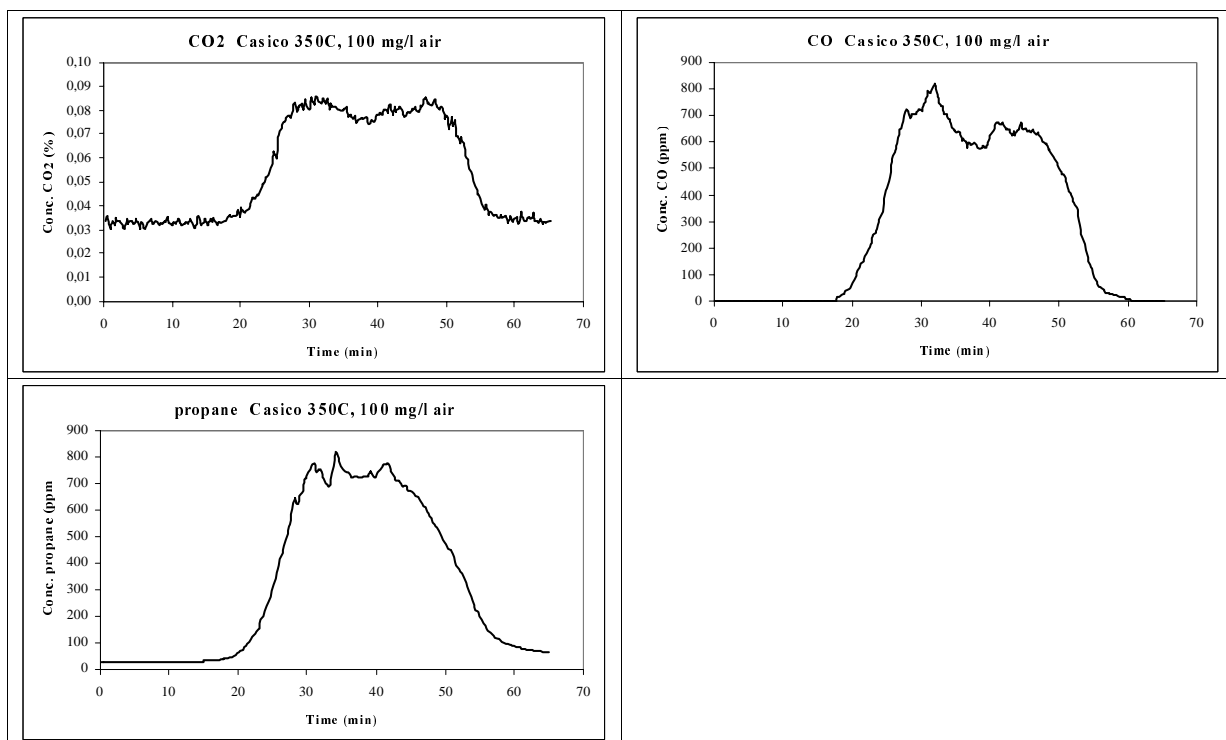


Figure 51 Compounds detected by FTIR and FID at 350 °C 100 mg/l air, CASICO.

The production of CO was also very low; the total mass produced was only 0.043 g, which resulted in a yield of 0.148 g/g combusted material. Only 0.3 g was combusted during the experiment, which may result in a relatively large error when calculating the yield. The average FID results are summarised in Table 23.

Table 23 Amounts of hydrocarbons, related to ppm propane, measured by FID at 350 °C 100 mg/l air, CASICO.

	Propane
Weight combusted (g):	0.3
Total mass (g)	0.054
Yield (g/g combusted material):	0.186
Max g/s:	0.0000
Max ppm propane:	820

The total mass of hydrocarbons produced was also quite low. The total mass produced was about half the mass produced at 650°C, resulting in a yield of 0.186 g/g combusted material, which is almost 8 times as much as the yields obtained from the experiments performed at 650°C, 100 mg/l air.

650°C, 400 mg/l air

No flaming combustion appeared during the experiment, instead the sample became dark, and started to bubble and boil. The total mass of CO₂ produced was 0.9 g and the yield was 0.18 g/g combusted material. The weight combusted was about the same as in the experiments performed at 650°C, 100 mg/l air. The average FTIR results are summarised in Table 24 and the species profiles are shown in Figure 52.

Table 24 Compounds detected and quantified by FTIR at 650 °C 400 mg/l air, CASICO.

	CO ₂	CO
Weight combusted (g):	4.8	
Total mass (g)	0.859	2.247
Yield (g/g combusted material):	0.178	0.466
Max g/s:	0.0006	0.0032
Max concentration:	1.1%	84941 ppm

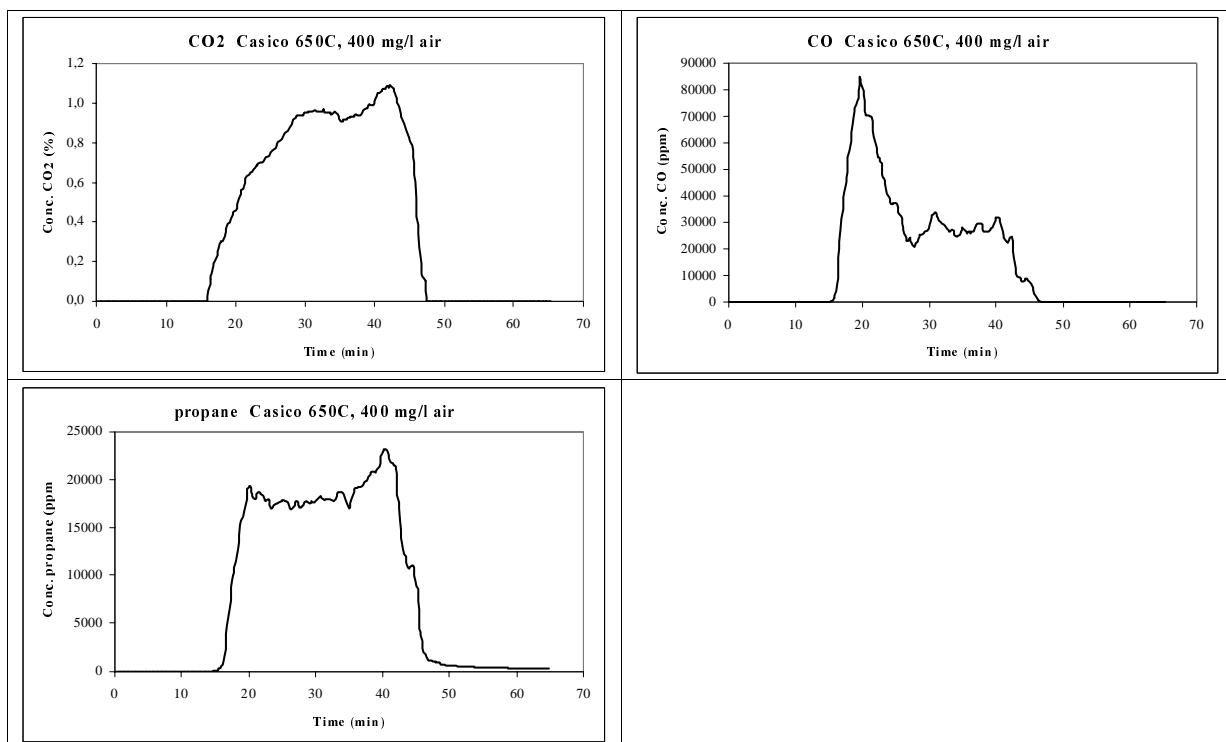


Figure 52 Compounds detected by FTIR and FID at 650 °C 400 mg/l air, CASICO.

The production of CO was considerable large in the beginning of the combustion process. However, when studying the spectra received during the analysis, it was discovered that some combustion product must have interfered with CO during the analysis (see Figure 53).

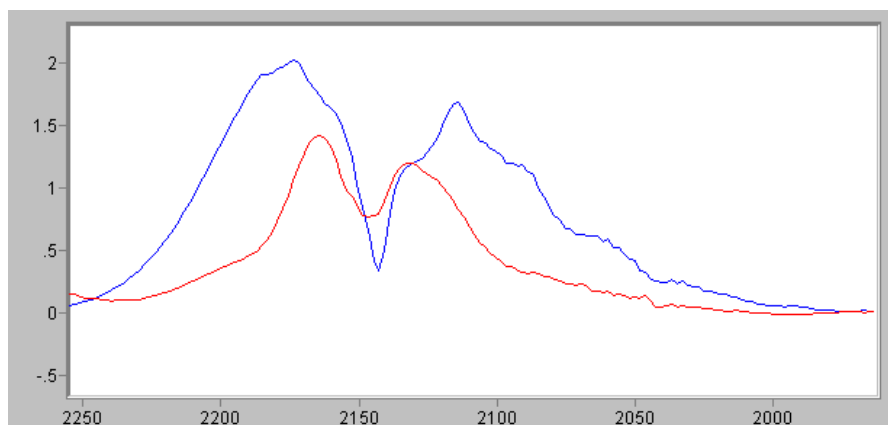


Figure 53 Received spectra (small peaks) and calibration spectra of 80 000 ppm (large peaks).

The smallest spectra are the one obtained from the experiment, and the larger is a calibration spectrum, where CO gas with a concentration of 80000 ppm was used. This calibration spectrum was used since the analysis results claimed the CO concentration to be about 84000 ppm.

As seen in Figure 53, the smaller curve does not represent the stated concentration, since the smaller curve would be much larger (wider and higher) if 84000 ppm was the true concentration. Therefore, another product from the decomposition of the sample must have been interfering with the measurement of the concentration of CO. Since the experiment was performed in vitiated atmosphere, it is reasonable to assume that it was high concentrations of some sort of non-combusted hydrocarbon that interfered with CO during the analysis. This interference resulted in an analysis result of the CO concentration that was said to be considerably higher than probably was the actual case during the experiment.

If the resulting spectrum is compared with calibration spectra of smaller concentrations (10000 ppm and 20000 ppm, see Figure 54), it seems reasonable that the real concentration of CO, in this case, is somewhere between these two, and not 84000 ppm as stated in the analysis results.

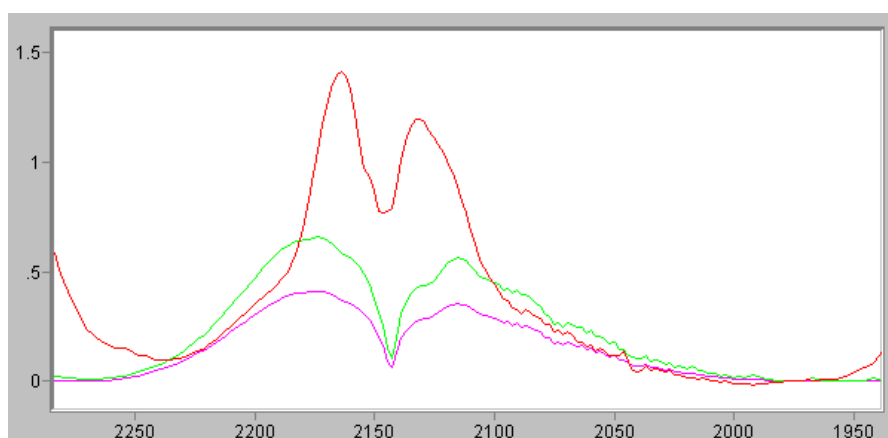


Figure 54 Received spectra (large peaks) and calibration spectra of 10 000 ppm and 20 000 ppm CO.

Which combustion product that was interfering with CO is unknown. One possible compound that may interfere with CO, and that may be produced during the decomposition of the CASICO material, is propyne, which has an absorbance in this region (strong absorbance at 2142 cm^{-1}).

If the concentration of CO actually was between 10000 ppm and 20000 ppm in this case is, however, very hard to say.

Table 25 Amounts of hydrocarbons, related to ppm propane, measured by FID at 650 °C 400 mg/l air, CASICO.

	propane
Weight combusted (g):	4.8
Total mass (g)	1.333
Yield (g/g combusted material):	0.277
Max g/s:	0.0010
Max ppm propane:	23090

As seen in Table 25 and Figure 52, the concentration, the total mass produced and the yield of non-combusted hydrocarbons was very high. Actually, the total mass produced and the yield is approximately 10 times as high as the results from the experiments performed at 650°C and 100 mg/l air. This would also support the theory that a hydrocarbon was interfering with the quantification of CO.

350°C, 400 mg/l air

No flaming combustion appeared during the experiment; instead the sample darkened, shrank and swelled. The weight loss during the experiment was below 0.1 g. This fact, and the fact that the maximum concentration of CO₂ detected was below 0.1%, indicates that the only combustion that occurred, if there was any, was smouldering combustion. It can be seen in Figure 55 that the increase of the production of CO₂ was very small during the experiment. The total mass of CO₂ produced was 0.1 g and the yield was 1.1 g/g combusted material. The high yield is due to the low weight combusted. The average FTIR results are summarised in Table 26.

Table 26 Compounds detected and quantified by FTIR at 350 °C 400 mg/l air, CASICO.

	CO₂	CO
Weight combusted (g):	0.1	
Total mass (g)	0.095	0.007
Yield (g/g combusted material):	1.053	0.080
Max g/s:	0.00003	0.000006
Max concentration:	0.1%	146 ppm

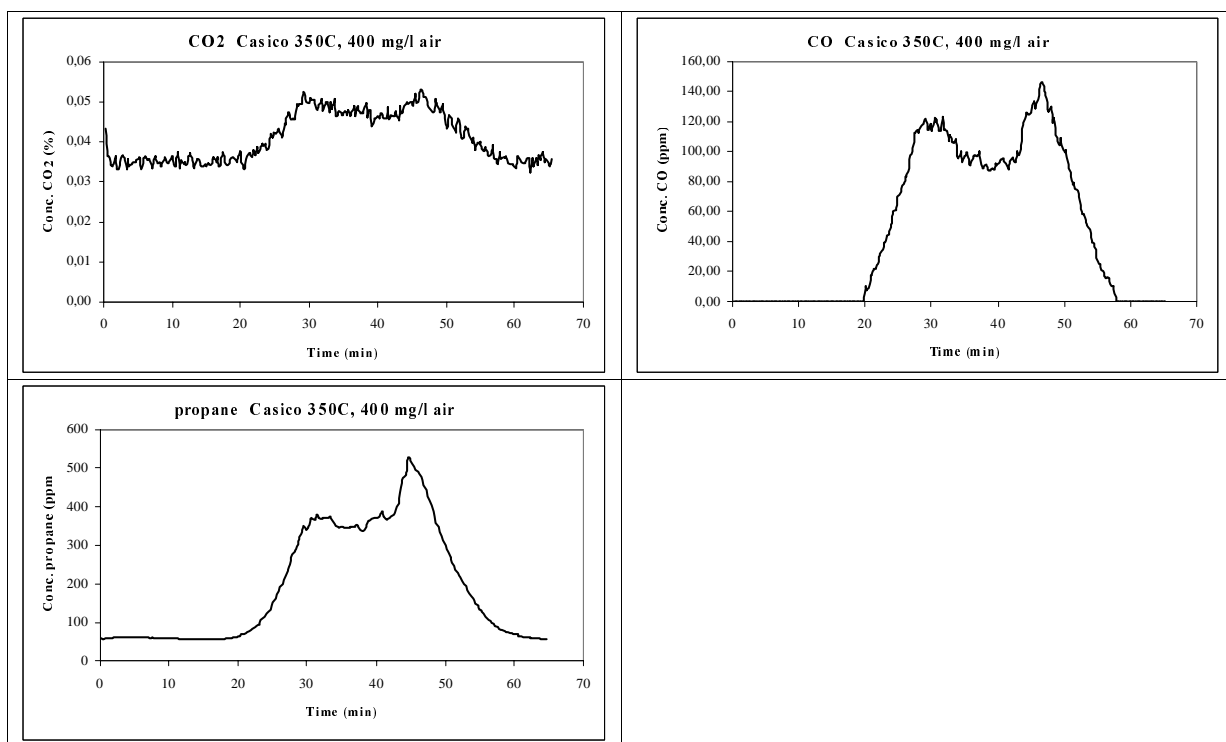


Figure 55 Compounds detected by FTIR and FID at 350 °C 400 mg/l air, CASICO.

The production of CO was quite low during this experiment. The maximum concentration reached was 146 ppm, and the total production was 0.007 g. This resulted in a yield of 0.080 g/g combusted material, due to the low weight combusted.

The production of hydrocarbons was very low, only reaching a peak level of 530 ppm. If this result is compared with the result from the experiment performed at 650 °C, 400 mg/l air, the difference is very large. The average FID results are summarised in Table 27.

Table 27 Amounts of hydrocarbons, related to ppm propane, measured by FID at 350 °C 400 mg/l air, CASICO.

	propane
Weight combusted (g):	0.1
Total mass (g)	0.032
Yield (g/g combusted material):	0.361
Max g/s:	0.0000
Max ppm propane:	530

Appendix 3 Methods of sampling, preparation and analysis, large scale experiments

The sampling system for all chemical species is shown in Figure 56.

The specific sampling, extraction and analysis methods for the major organic species are detailed below.

Volatile Organic Compounds (VOC)

Sampling: VOC measurements were performed by sampling on 200 mg Tenax adsorbent tubes. Two adsorbent lines in parallel were used, using two different sampling flows, nominally 10 and 50 ml/min. Each had a backup sampling tube also containing Tenax to collect any breakthrough.

Analysis: Adsorbents were analysed by thermal desorption (275°C) and High Resolution Gas Chromatography. The GC-system used a 60 m capillary column (CP-SIL5-CB), at the outlet split for both FID and MS detection. The total amount of VOCs was calculated by integrating the time range of 6-34, which for aromatic substances corresponds to the molecular size of 75 to 150 m/z, thus including benzene and naphthalene. Quantification was made on FID using toluene as a standard.

The identification of substances was done using MS and the NBS 75K mass spectra database as well as reference substances.

Polycyclic Aromatic Hydrocarbons (PAH)

Sampling: PAHs were collected using a sampling system consisting of a heated glass fibre filter, condenser with a condensate bottle, and an adsorbent cartridge containing XAD-2. The sampling flow was approx. 40 l/min, chosen to give air velocities in the probe inlet similar to air speeds in the duct (isokinetic sampling.)

Extraction: The extraction method is shown in Figure 57.

Analysis: The samples (filter, condensate and adsorbent) were prepared by using modified US EPA 3580 "Waste dilution" method. The determination of PAH was performed using the modified US EPA 8270 "Semi volatile organic compounds by gas chromatography /mass spectrometry (GC/MS): Capillary column technique" method. Quantification was carried out using an internal standard method, which implies that the results are compensated for losses due to sample preparation. Two internal standards were used: D₁₀-pyrene and D₁₂-perylene. Masses 128-228 were compensated based on the yield of D₁₀-pyrene, while masses 252-300 were compensated based on the yield of D₁₂-perylene.

Table 28 Compounds included in PAH-method.

Species	m/z	Comment
Naphthalene	128	Naphthalene results excluded and presented in the VOC part
Acenaphthylene	152	
Acenaphthene	154	
Fluorene	166	
Phenanthrene	178	
Anthracene	178	
Fluoranthene	202	
Pyrene	202	
Benzo(a)fluorene	216	
Benzo(b)fluorene	216	
Benzo(a)anthracene	228	
Chrysene/Triphenylene	228	
Benzo(b/j)fluoranthene	252	
Benzo(k)fluoranthene	252	
Benzo(e)pyrene	252	
Benzo(a)pyrene	252	
Perylene	252	
Indeno(1,2,3-cd)pyrene	276	
Benzo(g,h,i)perylene	276	
Dibenzo(a,h/a,c)anthracene	278	
Coronene	300	

Polychlorinated Dibenzodioxins/Dibenzofurans (PCDD/F)

Sampling: Same as PAH

Method: The determination was performed using High Resolution Gas Chromatography and Mass Fragmentography. Quantification was carried out using an internal standard method, implying that the results of the analysis were compensated for losses due to extraction and purification. The internal standards used were:

¹³C 2,3,7,8 TCDD for both TCDD and TCDF

¹³C 1,2,3,7,8 PnCDD for both PnCDD and PnCDF

¹³C 1,2,3,6,7,8 HxCDD for both HxCDD and HxCDF, HpCDD and HpCDF, and OCDD and OCDF

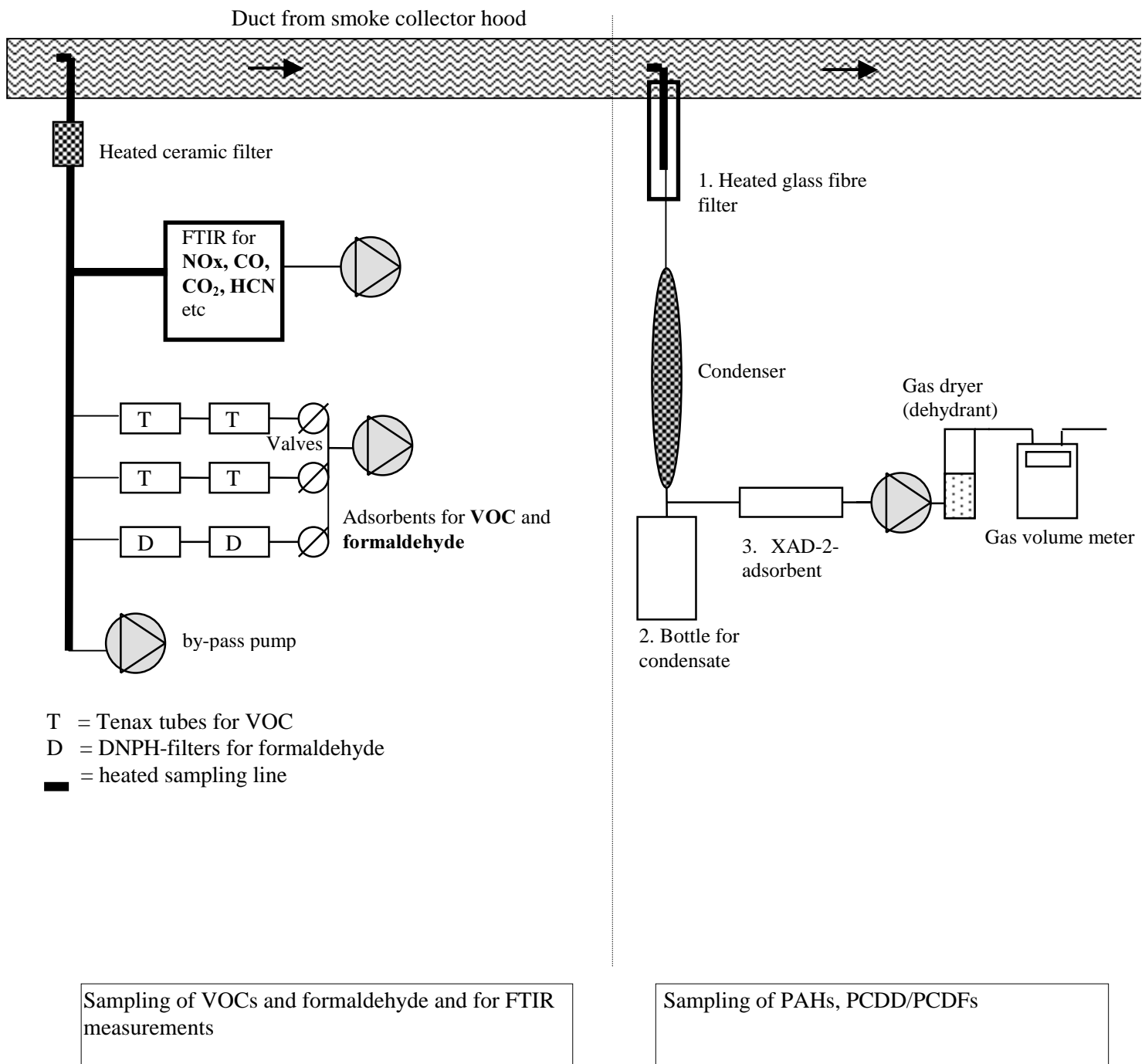


Figure 56 Schematic of sampling system for all chemical species in large scale cable tests in IEC 332-3 rig.

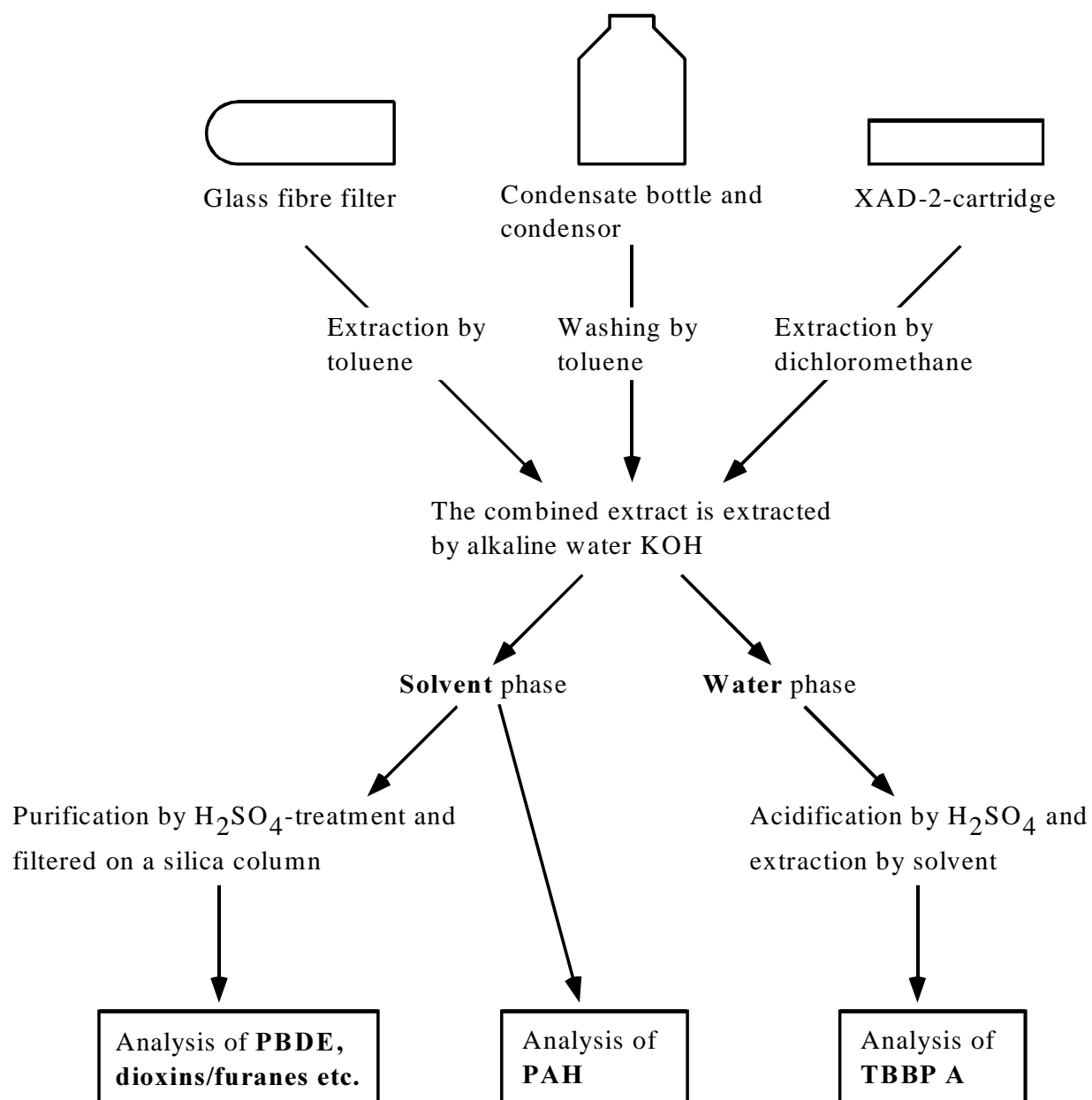


Figure 57 Schematic of extraction system for large organic species.

Appendix 4 Life-Cycle Inventory (LCI) Data

A4 1.1 Cables

Specification

In the study, two different types of cables have been used. The cable types represent one traditional PVC cable (EKK-light 3 G 1.5 from Nexans) and one ethylene based cable (CASICO, NOIK - light from NKT cables). The cables were selected to be equal in electrical function. Both cables have 3 conductors with a cross section area of 1.5 mm^2 . The exact production conditions for the cables and the composition of the cables are not public information and thus cannot be included in this report. However, high quality, representative data from the production was available in the project and included in the model due to a close co-operation with the cable producers. The information provided in this chapter is, however, only general.

Cables exist for many different purposes and each part of the cable has its own function. Figure 58 shows a cross section of the cables studied. The cables consisted of 4 different parts: conductors, insulation, bedding and sheathing. The insulation layer is simply an electrical insulation layer for the conductors. The cable is covered with a sheathing layer to protect the conductors from mechanical damage. Between the conductors/insulation and the sheathing layer is the bedding. The bedding fills the space between the sheathing and the conductors and makes the cable round. The material composition for the different parts of the cable can vary significantly depending on the specific function.

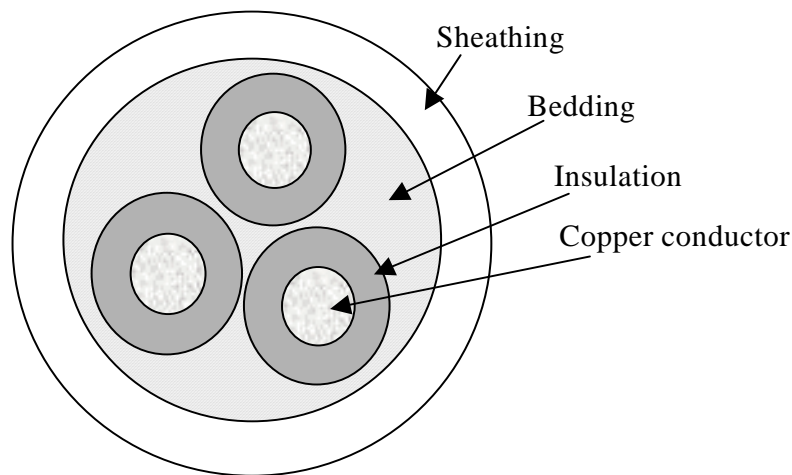


Figure 58 Cross section of the cables studied showing the different part of the cable.

The conductor materials can be either copper or aluminium based. In this case, copper cable has been selected for the study. As stated above two different isolation materials have been analysed representing a traditional halogen containing cable and a halogen free cable. The two selected cables have been chosen such that they have comparable fire performance.

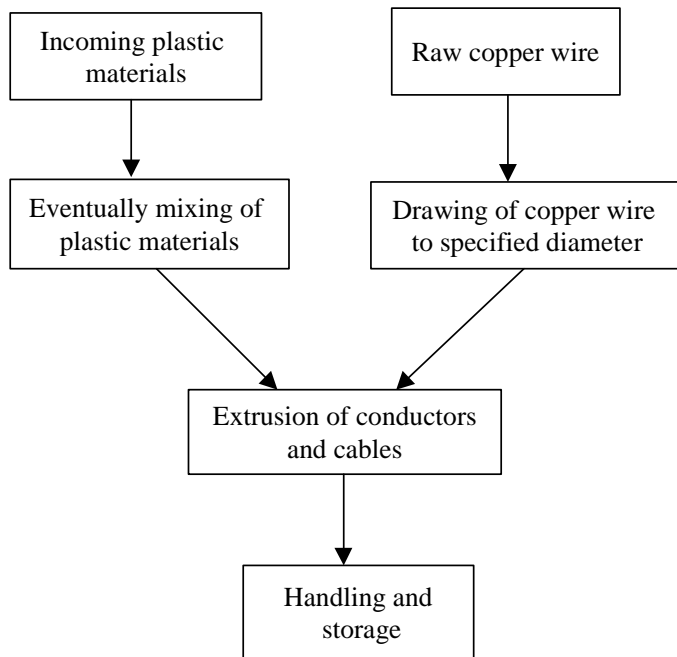
The main specification of the cables is shown in Table 29 below. As can be seen in this table the CASICO cable is specified in two ways. In the first CASICO column, the actual specification is detailed. Due to the fact that different manufacturers in different countries manufactured the cables the end results varied slightly in terms of the weight of conductor. To make the cables as comparable as possible in term of their function, the specification for the CASICO cable used in the LCA model was adjusted to be equivalent to the PVC cable. The details actually used for the CASICO cable in the LCA model are given under the heading “model specification”. All LCI data were calculated based on the model specifications and the fire emissions data were scaled down for the CASICO cable to correspond to the model amount of plastic.

Table 29 General specification of the cables used in this study.

Cable type	EKK-light 3 G 1.5	CASICO, NOIK - light 3 x 1.5	
		Actual specification	Model Specifications
Producer	Nexans	NKT cables	NKT cables
Conductor	Copper, 1.5 mm ²	Copper, 1.5 mm ²	Copper, 1.5 mm ²
# conductors	3	3	3
Main plastic materials	PVC	Polyethylene	Polyethylene
Plastic composition	PVC, Calcium carbonate, plasticiser, waxes and additives	EBA (ethylene and butyl acrylate co-polymer), polypropylene, silicone elastomer, calcium carbonate and additives	EBA (ethylene and butyl acrylate co-polymer), polypropylene, silicone elastomer, calcium carbonate and additives
Weight of conductor	39 kg/km	39.7 kg/km	39 kg/km
Weight of plastics	88 kg/km	89.3 kg/km	81 kg/km

Cable production at the cable production plant

The production route for the two different cable types is similar. The flow chart below shows the main step in the production at the cable production plant. The copper for the conductors is taken into the production as raw copper wire. In the production, the raw wire is drawn to the specified diameter. The copper conductors are covered with isolation, bedding and sheathing layers in different plastic extruders. The main energy source in the production of cables is electricity. Only marginal use of fuel oil and diesel oil occur in the production. The main use of diesel oil occurs in the transport of raw materials to the production site and in the distribution of the produced cables to users.



Copper production

In the LCI data that covers the production of copper, open mining in 2/3 of the production and sulphide ores (0.6% Cu) have been assumed. The mines are assumed to be located in Chile and the USA. The copper is delivered to Rotterdam. A base mix production of 80% virgin and 20% recycled copper has been assumed. World average data for 1993 has been used. Data includes transports from mine to factory gate. The LCI data for the production of Cu is summarised in Table 30.

Table 30 LCI data for production of copper. A small part (20 %) of recycled copper from external sources has been mixed in the production of virgin copper¹.

Values per 1 kg Copper			
Inputs		Outputs	
Energy resources		Emissions to air	
Coal	10.7 MJ	CO	0.00254 kg
Crude oil	67 MJ	CO ₂ , fossil	7.175 kg
Natural gas	14 MJ	NO _x	0.02 kg
Energy resources-renewable		SO ₂ ¹⁾	1.06 kg
Hydro Power	3.28 MJ	Emissions to water	
Resources		TSS	2.82 kg
Copper, Cu (ore)	0.8 kg	Materials/Products	
Resources/Products		Copper, Cu	1 kg
Copper, Cu (recycled)	0.2 kg	Solid wastes	
		Mineral waste	134 kg

1) The SO₂ emission is relatively high. The emission depends on the type of ore, fuels etc. and can vary significantly. Scrubbing of the exhaust gases can reduce the emission. The use of gas cleaning equipment also varies significantly from plant to plant.

PVC production

PVC plastics are used in all the plastic layers in the PVC cable. The production data for PVC are based on the LCI investigation performed by APME in 1992-1993 in combination with later updates of data^{2,3}. The main type of PVC used for cables are produced by suspension polymerisation. Thus, data for production by the suspension polymerisation process have been used. The data in that study are based on data supplied by the operators of 10 separate plants, which in total produce almost 1730000 tonne. The data includes raw material to factory gate and reflects average values for the processes. Modifications of the data have been made to cover emissions of mercury and dibenzodioxins. The mercury emissions are based on chlorine production with the mercury process in a modern Scandinavian plant. If chlorine production with the membrane process is used almost no mercury emission will be found. The LCI data for the production of PVC is shown in Table 31.

Table 31 LCI data for the production of virgin PVC from raw material to factory gate by suspension polymerisation. Electric power production is included in the figures ¹⁾.

Values per 1 kg PVC, virgin			
Inputs			Outputs
Chemicals			Emissions
KCl	0.0059	kg	TCDD eqv. ²⁾ 1.80E-15 kg
Sulphur, S	0.01	kg	Emissions to air
Energy resources			CH ₄ 0.0074 kg
Coal	3.97	MJ	Cl ₂ (air) 2.00E-06 kg
Crude oil	18.04	MJ	CO 0.0023 kg
Energy unspecified	0.1	MJ	CO ₂ , fossil 2 kg
Natural gas	26.95	MJ	HC (air) 0.0019 kg
Nuclear	5.8	MJ	HC aromatic (air) 6.00E-06 kg
Energy resources-renewable			HC chlorinated (air) 3.70E-05 kg
Hydro Power	0.9	MJ	HCl (air) 0.00015 kg
Materials/Products			Mercury, Hg (air) ²⁾ 2.70E-07 kg
Limestone CaCO ₃	0.01	kg	NO _x 0.0095 kg
Resources			Particles 0.0029 kg
Barite BaSO ₄	8.20E-05	kg	SO ₂ 0.0082 kg
Bauxite AlO(OH)	0.00044	kg	Emissions to water
Bentonite	3.20E-05	kg	Acids as H ion 4.80E-05 kg
Iron, Fe (ore)	0.00024	kg	BOD 8.50E-05 kg
Sand	0.00047	kg	Chloride ions 0.039 kg
Resources/Products			COD 0.00076 kg
NaCl	0.65	kg	HC (aq) 2.60E-05 kg
			HC chlorinated (aq) 1.00E-06 kg
			Mercury Hg (aq) ²⁾ 5.60E-08 kg
			Sodium ions (aq) 0.0078 kg

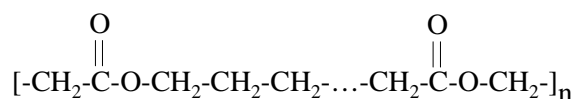
Table 31 (continued).

	Sulphate ions (aq)	0.0041	kg
	TSS	0.0017	kg
	Materials/Products		
	PVC virgin polymer	1	kg
	Solid wastes		
	Industrial waste	0.0042	kg
	Inert chemicals	0.011	kg
	Mineral waste	0.042	kg
	Regulated chemicals	0.005	kg
	Slag and Ash	0.0094	kg

- 1) Data source: Eco-Profiles of the European polymer industry, PVC (suspension polymerisation), Association of Plastics Manufacturers in Europe (APME), 1992-1993. Data from APME database. Selected data used.
- 2) Data refer to chlorine production with a modern mercury process. Data are modified figures based on Scandinavian plants. If chlorine production with the membrane process is used almost no mercury emission will be found.

Production of EBA

EBA stands for ethylene and butyl acrylate co-polymer. EBA is the main polymeric material in the CASICO cable. The EBA polymer is basically an ethylene polymer with an additional acrylate group in the polymer chain. The acrylate groups are relatively few, approximately 1 or 2 per 100 carbon atoms in the polymer chain. The principle structure is shown below.



No LCA data for an actual production of EBA has been found. However, the production is very similar to that of polyethylene. Data for polyethylene production has therefore been used as an approximation of production data for EBA. Data for Low Density Polyethylene (LDPE) from the APME study has been used. That production reflects well the production of EBA. An additional factor for the choice of data is that comparable data exist for both PVC and polyethylene from APME.

Data for energy consumption, material usage and emissions represent an average from all European cracker works and 36 polymerisation plants for polyethylene, see Table 32. Data gives the total values for production of 1 kg polyethylene, from raw materials extraction to final product. Energy consumption shows total usage, i.e. consumption of energy in the production processes as well as consumption of raw materials to the polymer itself, which is included in the product and counted as raw material. The data cover the time period 1989-92. The LCA study is from 1999⁴. In the data set, recovered energy has been calculated as a reduction of fuel oil use. Main gross raw material has been used. Data include production and feedstock energy.

Table 32 Inventory data for production of Low Density Polyethylene (LDPE) used as an approximation for EBA data ¹⁾.

Values per 1 kg EBA, virgin					
Inputs			Outputs		
Chemicals			Emissions to air		
CaSO ₄	4.00E-06	kg	CH ₄	0.0058	kg
Energy carriers			CO	0.0011	kg
Hydrogen	0.11	MJ	CO ₂ , biogenic	0.015	kg
Energy resources			CO ₂ , fossil	1.9175	kg
Coal	2.93	MJ	H ₂ S	1.00E-06	kg
Crude oil	29.9	MJ	HC (air)	0.0068	kg
Energy unspecified	0.06	MJ	HC aromatic (air)	2.90E-05	kg
Gas	42.42	MJ	HCl, air	5.60E-05	kg
Nuclear	3.7	MJ	NO _x	0.0096	kg
Peat	0.06	MJ	Particles	0.002	kg
Energy resources-renewable			SO ₂	0.0083	kg
Biomass fuel	0.08	MJ	Emissions to water		
Hydro Power	1.31	MJ	Acids as H ion	6.30E-05	kg
Materials/Products			BOD	0.00013	kg
Limestone CaCO ₃	0.0014	kg	Carbonate ions (aq)	4.20E-05	kg
Resources			COD	0.00047	kg
Bauxite AlO(OH)	0.00089	kg	Detergent/oil	0.00018	kg
Bentonite	4.50E-05	kg	Dissolved organics	3.70E-05	kg
Fluorspar CaF ₂	5.00E-06	kg	Dissolved solids	0.00016	kg
Iron, Fe (ore)	0.00026	kg	HC (aq)	4.50E-05	kg
Sand	0.00022	kg	NH ₄ (aq)	8.00E-06	kg
Resources/Products			Nitrate (aq)	5.00E-06	kg
Clay mineral	1.50E-05	kg	Phenol (aq)	3.00E-06	kg
NaCl	0.0013	kg	Phosphate as P ₂ O ₅ (aq)	4.00E-06	kg
			Sulphate ions (aq)	8.70E-05	kg
			Suspended solids (aq)	0.00022	kg
			Materials/Products		
			EBA virgin	1	kg
			Solid wastes		
			Industrial waste	0.0019	kg
			Mineral waste	0.022	kg
			Regulated chemicals	0.0015	kg
			Slag and Ash	0.007	kg

1) APME, I Boustead, Ecoprofiles of plastics and related intermediates. Published by APME, Brussels, 1999.

Production of polypropylene

Polypropylene is used as a minor component in the CASICO cable. Inventory data for the production of polypropylene has been developed by APME. Those data have also been used in this study ⁴. Data cover energy consumption, material usage and emissions, see Table 33. Data gives the total values for production of 1 kg polypropylene, from raw materials extraction to final product. Energy consumption shows total usage, i.e.

consumption of energy in the production processes as well as consumption of raw materials to the polymer itself, which is included in the product and counted as raw material. The data cover the time period 1992-93. Original LCA study is from 1999. In the data set, recovered energy has been calculated as a reduction of fuel oil use. Main gross raw material has been used. Data include production and feedstock energy.

Table 33: Inventory data for production of Polypropylene ¹⁾.

Values per 1 kg PP, virgin					
Inputs			Outputs		
Chemicals			Emissions to air		
CaSO ₄	3.00E-06	kg	CH ₄	0.0061	kg
Energy carriers			CO	0.00072	kg
Hydrogen	0.12	MJ	CO ₂ , biogenic	0.006	kg
Energy resources			CO ₂ , fossil	1.8077	kg
Coal	1.8	MJ	H ₂ S	1.00E-06	kg
Crude oil	41.41	MJ	HC (air)	0.0023	kg
Energy unspecified	0.04	MJ	HC aromatic (air)	3.00E-06	kg
Gas	31.29	MJ	HCl, air	3.30E-05	kg
Nuclear	1.94	MJ	NO _x	0.0096	kg
Peat	0.02	MJ	Particles	0.0015	kg
Energy resources-renewable			SO ₂	0.013	kg
Biomass fuel	0.04	MJ	Emissions to water		
Hydro Power	0.53	MJ	Acids as H ion	5.60E-05	kg
Materials/Products			BOD	3.40E-05	kg
Limestone CaCO ₃	0.00056	kg	Carbonate ions (aq)	3.10E-05	kg
Resources			COD	0.00018	kg
Bauxite AlO(OH)	0.0023	kg	Detergent/oil	6.90E-05	kg
Bentonite	2.60E-05	kg	Dissolved organics	6.50E-05	kg
Fluorspar CaF ₂	3.20E-05	kg	Dissolved solids	0.0001	kg
Granite	2.70E-05	kg	HC (aq)	5.10E-05	kg
Iron, Fe (ore)	0.00018	kg	NH ₄ (aq)	1.00E-05	kg
Sand	0.00013	kg	Nitrate (aq)	1.80E-05	kg
Resources/Products			Phenol (aq)	4.00E-06	kg
Clay mineral	1.40E-05	kg	Phosphate as P ₂ O ₅ (aq)	3.00E-06	kg
NaCl	0.0027	kg	Sulphate ions (aq)	5.60E-05	kg
			Suspended solids (aq)	0.00034	kg
			Materials/Products		
			Polypropylene (PP) 1		kg
			virgin		
			Solid wastes		
			Industrial waste	0.0021	kg
			Mineral waste	0.017	kg
			Regulated chemicals	0.011	kg
			Slag and Ash	0.0039	kg

1) APME, I Boustead, Ecoprofiles of plastics and related intermediates. Published by APME, Brussels, 1999.

Silicone elastomer production

No production data for silicon elastomers have been available in the project. Silicon is only used in small quantities in the CASICO formulation. Silicon has been treated as other additives and thus been approximated with the production of polyethylene, see the section on the production of EBA.

Production of plasticiser

Plasticisers are inert organic substances incorporated into a polymer to increase its flexibility and workability. Substantial amounts of plasticisers are used in flexible PVC plastic, the exact amount depending on the desired flexibility of the material. Many different organic substances can act as plasticisers. In this project plasticisers have been used in the production of PVC cables. The plasticisers are based on phthalate esters and referred to as high volume commodity plasticisers. Phthalate esters are diesters of phthalic anhydride, with a common chemical structure shown in Figure 59. They are made by reacting phthalic anhydride (PAN) with oxo alcohols to form esters. They differ in nature and length from the oxo alcohols (C_1 to C_{13}) from which they are made.

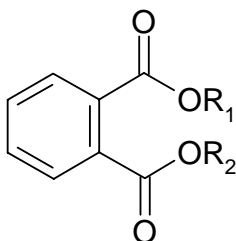


Figure 59 General chemical structure of phthalate esters

Process information and data for the production of phthalate esters are all from the report; Eco-profile of high volume commodity phthalate esters (DEHP/DINP/DIDP) ⁵.

The overall production route of phthalate esters includes the following process steps:

- Manufacturing of Phthalic anhydride from o-Xylene by oxidation.
- Manufacturing of C_8 olefins and C_9 olefins from Propene and Butenes in polygas or dimer units, produced in either steam cracking process or in petrochemical plants.
- Manufacturing of three different oxo alcohols: 2-Ethylhexanol from n-Butyraldehyde made by reacting Propene and Syngas, Isononyl alcohol from C_8 olefins and Syngas, and Isodecyl alcohol from C_9 olefins and Syngas.
- Manufacturing of the three high volume commodity phthalate esters by esterification between the Phthalic anhydride and the corresponding oxo alcohol.

Data for the actual production of the phthalate esters are supplied from 15 production plants (8 industrial companies) in Europe. All the supplied site data refer to 1998, with some exception of some site data referring to 1999. Data for starting raw materials are taken from APME eco-profile data (<http://lca.apme.org>). Electric power production data for the specific sites have been used. Inventory data for the production of 1 kg phthalate esters are shown in Table 34.

Table 34 Inventory data for production of phthalate plasticiser ⁵.

Values per 1 kg Phthalate plasticiser				
Inputs			Outputs	
Chemicals			Emissions to air	
CaSO ₄	1.10E-05	kg	Ammonia NH ₃ (air)	5.50E-07 kg
KCl	0.000343	kg	CFC/HCFC	4.20E-07 kg
Nitrogen, N ₂	0.037256	kg	CH ₄	0.004618 kg
Oxygen, O ₂	0.12578	kg	Cl ₂ (air)	1.00E-07 kg
Sulphur, S	0.00238	kg	CO	0.014939 kg
Energy resources			CO ₂ , fossil	1.8363 kg
Coal	1.06	MJ	H ₂ S	3.00E-06 kg
Crude oil	33.11	MJ	HC (air)	0.002317 kg
Energy unspecified, incl. recovered	-0.01	MJ	HC aromatic (air)	2.70E-05 kg
Natural gas	36.19	MJ	HC chlorinated (air)	7.60E-09 kg
Nuclear	1.32	MJ	HCl (air)	3.80E-05 kg
Energy resources-renewable			HF (air)	1.00E-06 kg
Hydro Power	0.24	MJ	Lead, Pb (air)	8.30E-08 kg
Materials/Products			Mercury, Hg (air)	9.90E-08 kg
Limestone CaCO ₃	0.002649	kg	N ₂ O	3.00E-06 kg
Resources			NO _x	0.006058 kg
Barite BaSO ₄	3.30E-05	kg	Organic acids (air)	0.000184 kg
Bauxite AlO(OH)	0.000477	kg	PAH	1.30E-08 kg
Bentonite	0.000114	kg	Particles	0.000712 kg
Gravel	4.70E-05	kg	Phthalate esters, air	7.10E-09 kg
Iron, Fe (ore)	0.000572	kg	Phthalic anhydride, air	6.00E-06 kg
Sand	8.30E-05	kg	SO ₂	0.005191 kg

Table 34 (cont.)

Resources/Products		Emissions to water	
Clay mineral	4.50E-05 kg	Acids as H ion	8.70E-05 kg
NaCl	0.01031 kg	Aluminium Al (aq)	1.00E-06 kg
		Ammonia NH ₃ (aq)	4.00E-05 kg
		Arsenic (aq)	4.00E-09 kg
		BOD	4.00E-05 kg
		Chloride ions	0.004344 kg
		COD	0.00049 kg
		Copper Cu (aq)	2.00E-06 kg
		Dissolved solids (aq)	0.000415 kg
		HC (aq)	7.20E-05 kg
		HC chlorinated (aq)	3.00E-06 kg
		Mercury Hg (aq)	1.10E-08 kg
		Nickel, Ni (aq)	7.40E-08 kg
		Phenol (aq)	2.00E-06 kg
		Sulphate ions (aq)	0.004043 kg
		TSS	4.00E-05 kg
		Zinc, Zn (aq)	9.60E-08 kg
		Materials/Products	
		Phthalate plasticiser	1 kg
		Solid wastes	
		Industrial waste	0.002038 kg
		Mineral waste	0.030712 kg
		Regulated chemicals	0.00263 kg
		Slag and Ash	0.004293 kg
		Waste to incineration	0.005011 kg
		Waste to recycling	0.00672 kg
		Waste, radioactive	5.90E-05 kg

Production of limestone filler

Limestone (CaCO₃) is commonly used as a filler in plastics. The life cycle inventory data are calculated based on information from a producer ⁶. The data includes material extraction, grinding and transportation. Data, calculated to factory gate, are summarised in Table 35.

Table 35 LCI data for production of limestone from resource extraction to factory gate. Main data have been used in the study ⁶.

Substance	Value	Unit
Emissions		
CO ₂	7.9	g/kg
SO ₂	0.04	g/kg
NO _x	0.031	g/kg
CO	0.0075	g/kg
HC (air)	0.021	g/kg
CH ₄	0.02	g/kg
As	0.042E-6	g/kg
Hg	0.00063E-6	g/kg
Cd	0.0063E-6	g/kg
Cr	0.017E-6	g/kg
Pb	0.42E-6	g/kg
Particles	0.021	g/kg
Waste, mineral	1000	g/kg
Energy		
Fossil fuel (oil)	0.023	MJ/kg
Electric power	0.22	MJ/kg

Cable use

The function of the cable is, in this case, to transport electricity to the final user of the electric energy. Thus, the cable itself does not use any energy during its life time. However, some losses of energy exist in the cable due to the impedance of the cable. The effect of this type of losses in the system is difficult to estimate due to the fact that it is difficult to estimate the average power use of the cable during its lifetime. The losses are, however, very small and have been neglected in this study.

A4 1.2 Fire

Introduction

The data source for the fire modules is the different fire experiments performed in this project (summarised in Chapter 4) and in the previous TV-LCA case study ⁷. As the fire emissions data from the experiments have been summarised elsewhere, the inventory description of the fire modules describes the life cycle representation of the fire experiments. In the different fire modules in the model the fire experiments have been translated into a mathematical form to be used in the model calculations. In the following sections the calculations for the different modules together with a short module description can be found. Recall that the LCI data for fire emissions for the CASICO cable have been scaled to correlate to the amount of plastic in the “model cable” defined in Table 29.

PVC Cable Fire (ventilated and vitiated)

The data describe a ventilated and a vitiated PVC cable fire where no spreading of the fire beyond the cables occurs. Data are based on fire experiments performed in the

project. The emission of HCN, NH₃, SO₂ and NO_x did not exceed the limit of quantification. Table 36 summarises the parameters used in the fire module while Table 37 shows the equations used to simulate the results of a well-ventilated PVC cable fire and Table 38 the equivalent results for a vitiated fire.

Table 36 Parameter specification for the PVC Cable Fire module.

Inputs		Outputs	
Materials/Products		Emissions	
Copper, Cu	kg	TCDD eqv.	kg
PVC plastics	kg	Emissions to air	
Products		CO	kg
Cable	km	CO ₂ , fossil	kg
Cable Burned	km	HCl (air)	kg
Replaced Cable	km	PAH	kg
		HC (air)	kg
		Solid wastes	
		Fire waste (unburnt and ash)	kg

Table 37 Equations defining the simulation results of the ventilated PVC Cable Fire.

Equations ¹⁾
Emissions
TCDD eqv.=1.865E-007*Cable Burned
Emissions to air
CO=2.2*Cable Burned
CO ₂ , fossil=109.8*Cable Burned
HCl (air)=21.7*Cable Burned
PAH=0.0595*Cable Burned
HC (air)=0.2302*Cable Burned
Products
Cable Burned=0.5*Cable
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Copper, Cu+0.54*PVC plastics

1) Data from the cable fire experiments in the project.

Table 38 Equations defining the simulation results of the vitiated PVC Cable Fire.

Equations ¹⁾
Emissions
TCDD eqv.=1.686E-007*Cable Burned
Emissions to air
CO=2.32*Cable Burned
CO ₂ , fossil=109.8*Cable Burned
HCl (air)=21.7*Cable Burned
PAH=0.0534*Cable Burned
HC (air)=0.2032*Cable Burned
Products
Cable Burned=0.5*Cable
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Copper, Cu+0.54*PVC plastics
1) Data from the cable fire experiments in the project.

Secondary fires - PVC Cable

Data from the vitiated PVC cable fire experiment have been used. See the section above on the PVC Cable Fire (ventilated and vitiated) above for specific input details.

PVC Cable/House Fire and PVC Cable/Room Fire

This module covers data from a cable fire where the fire has spread beyond the original cable fire to a room or an entire house. In the model, the fire spreading can be set to include a specific area of the house. The variable list and the calculation model are shown in Table 39 and Table 40. The data used in the model originates from fire experiments of room fires in the TV case study ⁷. Data has been used for an ordinary room fire with no or low presence of flame retardants. Data reflects both emissions that depend on the fire conditions and that depend on the composition of the burned materials. Data has been adjusted for the specific cable application and additional data from the cable experiments have been included. The emission of dioxins, expressed as TCDD equivalents, has been allocated to the chlorine content in the cables. The special implication of this method is discussed in the Incineration part of this chapter. The emission of NO_x did not exceed the limit of quantification.

Table 39 Parameter specification for the PVC Cable/House-Room Fire modules.

Inputs		Outputs	
Chemicals		Emissions	
Gypsum CaSO_4	kg	TCDD eqv.	kg
Materials/Products		Emissions to air	
Brass	kg	Ammonia NH_3 (air)	kg
Burnable material	kg	CO	kg
Burned material	kg	CO_2 , fossil	kg
Copper, Cu	kg	HC (air)	kg
Cotton DS	kg	HCl (air)	kg
EPDM	kg	HCN	kg
Iron, Fe	kg	PAH	kg
Leather DS	kg	SO_2	kg
Paper DS	kg	XCO_2 , fossil, burnable	kg
Polyethene (PE)	kg	Solid wastes	
Polypropene (PP)	kg	Fire waste (unburnt and ash)	kg
Polystyrene (HIPS)	kg		
Polyurethane (PUR)	kg		
PVC plastics	kg		
Wood DS	kg		
Wool DS	kg		
Products			
Cable	km		
Replaced Cable	km		
Resources			
Marble	kg		
Resources/Products			
Concrete	kg		
Macadam	kg		
Rockwool	kg		
Specifications			
House fire area	m^2		
House replacement area	m^2		
Interior fire area	m^2		

Table 40 Equations defining the simulation results of the PVC Cable/House-Room Fires⁷.

Equations
Emissions
TCDD eqv.=1.686E-007*Cable
Emissions to air
Ammonia NH ₃ (air)=0.000894*Burned material
CO=0.034*Burned material
CO ₂ , fossil=XCO ₂ , fossil, burnable
HC (air)=0.000894*Burned material
HCl (air)=0.25*PVC plastics
HCN=0.00157*Burned material
PAH=0.000404*Burned material
SO ₂ =0.0059*Burned material+0.047*Gypsum CaSO ₄
XCO ₂ , fossil, burnable=3.14*EPDM+3.14*Polyethene (PE)+3.14*Polypropene (PP)+3.37*Polystyrene (HIPS)+2.27*Polyurethane (PUR)+1.24*PVC plastics
Materials/Products
Burnable material=Cotton DS+EPDM+Leather DS+Paper DS+Polyethene (PE)+Polypropene (PP)+Polystyrene (HIPS)+Polyurethane (PUR)+PVC plastics+Wood DS+Wool DS
Burned material=Burnable material
Products
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Burnable material-Burned material+Gypsum CaSO ₄ +Brass+Copper, Cu+Iron, Fe+Marble+Concrete+Rockwool
Specifications
House fire area=484*Cable
House replacement area=242*Cable
Interior fire area=484*Cable

CASICO Cable Fire (ventilated and vitiated)

This data describes a well-ventilated and a vitiated CASICO cable fire where no spreading of the fire beyond the cables occurs. Data are based on fire experiments performed in the project. The emission of HCN, NH₃, SO₂ and NO_x did not exceed the limit of quantification. Table 41 summarises the parameters used in the fire module while Table 42 shows the equations used to simulate the results of a well-ventilated cable fire and Table 43 the equivalent results for a vitiated fire.

Table 41 Parameter specification for the CASICO Cable Fire module.

Inputs		Outputs	
Materials/Products		Emissions	
CASICO plastics	kg	TCDD eqv.	kg
Copper, Cu	kg	Emissions to air	
Products		CO	kg
Cable	km	CO ₂ , fossil	kg
Cable Burned	km	PAH	kg
Replaced Cable	km	HC(air) ¹⁾	kg
		Solid wastes	
		Fire waste (unburnt and ash)	kg

1) Including VOC.

Table 42 Equations defining the simulation results of the ventilated CASICO Cable Fire¹⁾.

Equations
Emissions
TCDD eqv.=8.35E-009*Cable Burned
Emissions to air
CO=0.61*Cable Burned
CO ₂ , fossil=140.9*Cable Burned
PAH=0.012*Cable Burned
HC(air)=0.063*Cable Burned
Products
Cable Burned=0.5*Cable
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Copper, Cu+0.7*CASICO plastics

1) Data from the cable fire experiments in the project.

Table 43 Equations defining the simulation results of the vitiated CASICO Cable Fire¹⁾.

Equations
Emissions
TCDD eqv.=1.44E-008*Cable Burned
Emissions to air
CO=2.6*Cable Burned
CO ₂ , fossil=140.9*Cable Burned
PAH=0.036*Cable Burned
HC(air)=0.29*Cable Burned
Products
Cable Burned=0.5*Cable
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Copper, Cu+0.7*CASICO plastics

1) Data from the cable fire experiments in the project.

Secondary fires - CASICO Cable

Data from the vitiated CASICO cable fire experiment have been used. See the section concerning CASICO Cable Fires (ventilated and vitiated) above for more details.

CASICO Cable/House Fire and CASICO Cable/Room Fire

This module covers data from a CASICO cable fire where the fire has spread beyond the original cable to a room or an entire house. In the model, the fire spreading can be set to include a specific area of the house. The variable list and the calculation model are shown in Table 44 and Table 45. The data used in the model originate from fire experiments of room fires in the TV case study⁷. Data has been used for an ordinary room fire with no or low presence of flame retardants. Data reflects both emissions that depend on the fire conditions and that depend on the composition of the burned materials. Data has been adjusted for the specific cable application and additional data from the cable experiments have been included. In principle, the CASICO cable should be totally halogen free. However, in the analysis of the cable contents, traces of chlorine have been found also in this CASICO cable (0.016 %-w of the cable). It is unclear how the chlorine contamination of the material has occurred but it is most probable that the chlorine is present as a contaminant in the filler material. Thus, for the CASICO cable the results have been adjusted for chloride content. The emission of dioxins, expressed as TCDD equivalents, has been allocated to the chlorine content in the cables. The special implication of this method is discussed in the Incineration part of this chapter. The emission of NO_x did not exceed the limit of quantification.

Table 44 Parameter specification for the CASICO Cable/House-Room Fire modules.

Inputs		Outputs	
Chemicals		Emissions	
Gypsum CaSO_4	kg	TCDD eqv.	kg
Materials/Products		Emissions to air	
Brass	kg	Ammonia NH_3 (air)	kg
Burnable material	kg	CO	kg
Burned material	kg	CO_2 , fossil	kg
CASICO plastics	kg	HC (air)	kg
Copper, Cu	kg	HCl (air)	kg
Cotton DS	kg	HCN	kg
EPDM	kg	PAH	kg
Iron, Fe	kg	SO_2	kg
Leather DS	kg	XCO_2 , fossil, burnable	kg
Paper DS	kg	Solid wastes	
Polyethene (PE)	kg	Fire waste (unburnt and ash)	kg
Polypropene (PP)	kg		
Polystyrene (HIPS)	kg		
Polyurethane (PUR)	kg		
PVC plastics	kg		
Wood DS	kg		
Wool DS	kg		
Products			
Cable	km		
Replaced Cable	km		
Resources			
Marble	kg		
Resources/Products			
Concrete	kg		
Macadam	kg		
Rockwool	kg		
Specifications			
House fire area	m^2		
House replacement area	m^2		
Interior fire area	m^2		

Table 45 Equations defining the simulation results of the CASICO Cable/House-Room Fires⁷.

Equations
Emissions
TCDD eqv.=1.44E-008*Cable
Emissions to air
Ammonia NH ₃ (air)=0.000894*Burned material
CO=0.034*Burned material
CO ₂ , fossil=XCO ₂ , fossil, burnable
HC (air)=0.000894*Burned material
HCl (air)=0.25*PVC plastics
HCN=0.00157*Burned material
PAH=0.000404*Burned material
SO ₂ =0.0059*Burned material+0.047*Gypsum CaSO ₄
XCO ₂ , fossil, burnable=3.14*EPDM+3.14*Polyethene (PE)+3.14*Polypropene (PP)+3.37*Polystyrene (HIPS)+2.27*Polyurethane (PUR)+1.41*PVC plastics+1.74*CASICO plastics
Materials/Products
Burnable material=Cotton DS+EPDM+Leather DS+Paper DS+Polyethene (PE)+Polypropene (PP)+Polystyrene (HIPS)+Polyurethane (PUR)+PVC plastics+Wood DS+Wool DS+Casico plastics
Burned material=Burnable material
Products
Replaced Cable=0.5*Cable
Solid wastes
Fire waste (unburnt and ash)=Burnable material-Burned material+Gypsum CaSO ₄ +Brass+Copper, Cu+Iron, Fe+Marble+Concrete+Rockwool+0.37*CASICO plastics
Specifications
House fire area=484*Cable
House replacement area=242*Cable
Interior fire area=484*Cable

A4 1.3 Replacement of burned material

Introduction

A fire can be considered as a process where the lifetime of a product is shortened. Thus, the product has to be replaced earlier than for the normal ageing process. This results in an increased product production with a corresponding increase in energy use and emission release. As an average figure a 50 % reduction of the lifetime has been assumed. However, the risk for a fire based on a product is probably largest in the beginning and at the end of the life-time according to the “bath tub” shaped product failure curve.

Cable replacement

The cable replacement figures are equal to the production figures used for the production of new cables. However, the figures will be reduced with 50 % to reflect the lifetime shortening (only 50 % of the life-time of the cables will be replaced). The effect in the model of the cable replacement will thus be an overall increased cable production.

House replacement

The module covers the production of a wooden domestic dwelling from raw material to the factory gate. The house is a prefabricated standard Swedish dwelling produced by Myresjö (Villa växa D548) ⁸. The house area is 121 m². Data covers only the production of the house and thus not decoration, furnishing, equipment (stove, refrigerator, freezer, washing machine etc.). The parameters used in this part of the LCI are summarised in Table 46.

Table 46 LCI data for production of a house excluding interior decoration such as furniture etc. The house is a wooden dwelling with 121 m² area ¹⁾.

Values per 1 House					
Inputs			Outputs		
Chemicals			Emissions to air		
Gypsum CaSO ₄	5107	kg	Aldehydes (air)	1.1	kg
Energy carriers			Ammonia NH ₃ (air)	6.6	kg
Electric power	36850	MJ	CO	89	kg
Energy resources			CO ₂ , fossil	14400	kg
Coal	59840	MJ	HC (air)	85	kg
Crude oil	29890	MJ	HC chlorinated (air)	0.18	kg
Natural gas	5190	MJ	HCl (air)	0.11	kg
Materials/Products			Metals (air)	0.004	kg
Iron, Fe	1109	kg	N ₂ O	0.19	kg
Resources			NO _x	96	kg
Copper, Cu (ore)	56	kg	Particles	20	kg
Marble	118	kg	SO ₂	48	kg
Timber	14000	kg	Emissions to water		
Zinc, Zn (ore)	5	kg	Acids as H ion	0.12	kg
Resources/Products			BOD	0.16	kg
Concrete	52712	kg	Chloride ions	15	kg
Macadam	71940	kg	COD	1.2	kg
Rockwool	3666	kg	Metals (aq)	0.17	kg

Table 46 (cont.)

Specifications			N, total (aq)	0.04	kg
House area	121	m ²	Oil, unspec. (aq)	0.08	kg
			Sodium ions (aq)	1.8	kg
			Sulphate ions (aq)	0.52	kg
			TSS	0.76	kg
			Materials/Products		
			House	1	house
			Solid wastes		
			Hazardous waste	4	kg
			Industrial waste	1203	kg
			Mineral waste	2050	kg
			Slag and Ash	0.38	kg
			Specifications		
			House area	121	m ²

1) Environmental declaration, Myresjöhus AB. Declaration performed by TRÅTEK, Martin Erlandsson⁸.

Replacement of interior materials

This module covers the production of the interior material in the house. That material has to be replaced after a fire. Only 50 % of the production burden has been allocated for the replacement due to the average lifetime of the furniture that is burned in the fire. A house can, of course, contain a lot of different material. However, these calculations are based on the interior specifications for the fire experiments in the TV case study⁷. The LCA production data for the materials are estimations. This module specifies the incoming and outgoing material for the production of the specified 16 m² rooms. This internal load will also reflect a certain fire energy load. LCI modules for the production of the most significant materials (paper, wood and polyurethane) are also added to the interior material production module. By calculating the interior load per area the fire area can be scaled when an equal interior material load is assumed. The interior load can, however, deviate significantly in specific parts of a house, such as washing rooms and kitchens. The electric power used for the production of the different materials has been estimated to 30 kWh for the entire room (16 m²). The material and energy specification is shown in Table 47.

Table 47 Specifications for the interior material production ¹⁾.

Values per 16 m ² House area					
Inputs			Outputs		
Energy carriers			Materials/Products		
Electric power	108	MJ	Armchair	38	kg
Materials/Products			Books	218	kg
Cotton DS	15	kg	Bookshelf	40	kg
Leather DS	10	kg	Carpet	8	kg
Paper DS	218	kg	Coffee table	26	kg
Polyurethane (PUR)	30	kg	Corner bookshelf	52	kg
Wood DS	178	kg	Curtains	5	kg
Wool DS	8	kg	Sofa	72	kg
			Specifications		
			House area	16	m ²

1) Data calculated by IVL and SP.

A4 1.4 Waste handling

Landfill

The model unit describes the landfill of cables and cable materials. To understand the processes in a landfill and thus to calculate the specific emissions is a very difficult task and can only be done in general terms. The degradation of plastics in landfills in relation to the LCA concept has been studied in several projects^{7, 11}. During the last years at least two deeper studies have been made where emissions from landfilled PVC have been studied by literature survey, lysimeter tests and full-scale tests^{12, 13}. The landfill data are derived from several studies and different aspects have been taken into consideration.

In this study, the emission data are based on a surveyable time period of 100 years. Thus, the emissions represent correspond to the emissions released during the first 100 years of the landfill. Only a minor part of the emissions will be released to the recipient during this period. The major part of the materials is still in the landfill after 100 years and will be released/broken down during the following time period. Of the original polymer materials, only 3 % have been assumed to be broken down during the first 100 years in the landfill. However, during the same period of time 80 % of the plasticisers in the PVC cable have been assumed to be broken down. Limestone filler in the plastic materials has been assumed to be stable in the landfill.

Data in the model reflect a situation with methane recovery for energy production. Methane recovery is used in landfills when the methane formation is high. This occurs in the beginning of the lifetime of the landfill. During this time, only a small fraction of the plastics have been broken down. It has therefore been assumed that only 10 % of the methane formed from the polymer materials and 25 % of the methane from the plasticisers (only for the PVC cable) have been collected by the methane recovery system. Further, it has been assumed that 10 % of the methane emitted from the landfill has been oxidised to CO₂ already in the landfill. A model has been used to calculate the parameters in the landfill module. Values for PVC with 25 % DEHP (di(2-

ethylhexyl)phthalate) have been used. The figures are approximate. In Table 48 and Table 50 the module parameters are defined and the equations are shown in Table 49 and Table 51.

Table 48 Parameter specification for the PVC cable landfill module.

Inputs		Outputs	
Materials/Products		Emissions to air	
Copper, Cu	kg	CH ₄	kg
PVC plastics	kg	CO ₂ , fossil	kg
Products		Vinyl chloride monomer	kg
Cable	km	Emissions to water	
Solid wastes		BOD	kg
Slag and Ash	kg	COD	kg
		Copper Cu (aq)	kg
		Phthalate	kg
		Energy carriers	
		Energy steam/heat	MJ
		Energy fuels	
		CH ₄ fuel energy	MJ
		CH ₄ fuel mass	kg
		Solid wastes	
		Industrial waste	kg
		Waste, Cu remainder	kg
		Waste, plastic remainder	kg

Table 49 Equations defining the simulation results of the PVC cable landfill module
1)

Equations
Emissions to air
$\text{CH}_4 = 0.057 * \text{PVC plastics}$
$\text{CO}_2, \text{ fossil} = 0.185 * \text{PVC plastics}$
$\text{Vinyl chloride monomer} = 4.8\text{E-}007 * \text{PVC plastics}$
Emissions to water
$\text{BOD} = 0.00072 * \text{PVC plastics}$
$\text{COD} = 0.00289 * \text{PVC plastics}$
$\text{Copper Cu (aq)} = 7.5\text{E-}005 * \text{Copper, Cu}$
$\text{Phthalate} = 0.00016 * \text{PVC plastics}$
Energy carriers
$\text{Energy steam/heat} = 0.8 * \text{CH}_4 \text{ fuel energy}$
Energy fuels
$\text{CH}_4 \text{ fuel energy} = 50 * \text{CH}_4 \text{ fuel mass}$
$\text{CH}_4 \text{ fuel mass} = 0.02 * \text{PVC plastics}$
Solid wastes
$\text{Industrial waste} = \text{Copper, Cu} + \text{PVC plastics} + \text{Slag and Ash}$
$\text{Waste, Cu remainder} = \text{Copper, Cu} - \text{Copper Cu (aq)}$
$\text{Waste, plastic remainder} = 0.84 * \text{PVC plastics}$
1) Data calculated by IVL ⁷ .

Table 50 Parameter specification for the CASICO cable landfill module.

Inputs	Outputs
Materials/Products	Emissions to air
CASICO plastics kg	CH_4 kg
Copper, Cu kg	$\text{CO}_2, \text{ fossil}$ kg
Products	Emissions to water
Cable km	BOD kg
Solid wastes	COD kg
Slag and Ash kg	Copper Cu (aq) kg
	Energy carriers
	Energy steam/heat MJ
	Energy fuels
	$\text{CH}_4 \text{ fuel energy}$ MJ
	$\text{CH}_4 \text{ fuel mass}$ kg
	Solid wastes
	Industrial waste kg
	Waste, Cu remainder kg
	Waste, plastic remainder kg

Table 51 Equations defining the simulation results of the CASICO cable landfill module ¹⁾.

Equations
Emissions to air
$\text{CH}_4 = 0.01 * \text{CASICO plastics}$
$\text{CO}_2, \text{ fossil} = 0.019 * \text{CASICO plastics}$
Emissions to water
$\text{BOD} = 9.5\text{E-}005 * \text{CASICO plastics}$
$\text{COD} = 0.00038 * \text{CASICO plastics}$
$\text{Copper Cu (aq)} = 7.5\text{E-}005 * \text{Copper, Cu}$
Energy carriers
$\text{Energy steam/heat} = 0.8 * \text{CH}_4 \text{ fuel energy}$
Energy fuels
$\text{CH}_4 \text{ fuel energy} = 50 * \text{CH}_4 \text{ fuel mass}$
$\text{CH}_4 \text{ fuel mass} = 0.00124 * \text{CASICO plastics}$
Solid wastes
$\text{Industrial waste} = \text{Copper, Cu} + \text{Casico plastics} + \text{Slag and Ash}$
$\text{Waste, Cu remainder} = \text{Copper, Cu} - \text{Copper Cu (aq)}$
$\text{Waste, plastic remainder} = 0.98 * \text{CASICO plastics}$

1) Data calculated by IVL ⁷.

Incineration

The inventory data for the incineration process covers the incineration of cables and disassembled materials from cables. The parameters used in the calculations can be found in Table 52 and Table 54 and the calculation models are presented in Table 53 and Table 55. It is assumed that the cables and cable materials from the disassembly process are incinerated in standard waste incinerators with a relatively high degree of flue gas cleaning. The cables are only a part of the total waste flow to the incinerator. The total amount of different wastes also results in a total amount of emissions from the incinerator. Thus, to be able to calculate the emissions from the cables, the total emission must be allocated to the different types of waste input. This method chosen is a typical multi-input allocation. The methodology used in the study for the allocation is described in reference 10.

Wherever possible the different emissions have been calculated directly from the material content e.g. CO_2 and HCl emissions. Emissions that are related to the combustion conditions in the incinerator have been calculated based on an assumed emission level from a typical incinerator, which has been allocated to the cables or to the cable materials. The emission of CO has been allocated to the carbon content of the materials in the cable. The emissions of hydrocarbons (HC) and PAH have been allocated to the total amount of organic materials i.e. total amount of plastic materials. The emission of particles has been allocated to the total amount of waste that can contribute to the particle formation in the incinerator. The emissions of dibenzodioxins (TCDD) are perhaps the most difficult parameters to allocate. In this study an allocation based on the content of chloride in the cable materials has been used*. The emission levels of dibenzodioxins

* An alternative allocation procedure is to recognise that increased dioxin emissions with increased chlorine input to an incinerator only occur with low chlorine concentration in the incinerator. Normally, the chlorine concentration in waste is higher than this threshold level. Thus, increased chlorine input due to PVC incineration will not result in a direct increase in dioxin emission and cont. on next page

from a typical waste incinerator have been used to calculate a typical dioxin emission per input amount of chloride. The chloride input has then been used to calculate the emissions. The assumption is only valid for a particular chloride load of the incinerator. The allocation used does not provide an entirely accurate picture of the dioxin emission situation but will act as an indication of the emission levels. The allocation background of the dioxin data is an important factor to bear in mind when the results are interpreted.

The energy production from the incineration has also been calculated. In the incineration process the energy content of the different combustible materials in cables can be transformed into useful energy, for example, for use in district central heating. The energy produced can therefore replace other types of fuels and thereby reduce emissions and save energy resources.

Table 52 Parameter specification for the PVC cable incineration module.

Inputs	Outputs
Materials/Products	Chemicals
Copper, Cu kg	Cl kg
PVC plastics kg	Emissions
Products	TCDD eqv. kg
Cable km	Emissions to air
	CO kg
	CO ₂ , fossil kg
	HC (air) kg
	HCl (air) kg
	NO _x kg
	PAH kg
	Particles kg
	Emissions to water
	Copper Cu (aq) kg
	Energy
	Heat of combustion MJ
	Energy carriers
	Energy steam/heat MJ
	Materials/Products
	Copper, Cu kg
	Solid wastes
	Slag and Ash kg

thus no dioxin emission need be allocated to the PVC incineration. This allocation principle, however, results in a situation where the dioxin emissions are only allocated to other chlorine containing waste. This allocation principle has *not* been used in the project.

Table 53 Equations defining the simulation results of the PVC cable incineration module. Data are based on controlled HCl emissions (3 % of formed HCl is emitted to the recipient) ¹⁾.

Equations
Chemicals
$Cl = 0.239 * PVC \text{ plastics}$
Emissions
$TCDD \text{ eqv.} = 1.004E-010 * Cl$
Emissions to air
$CO = 0.00035 * CO_2, \text{ fossil}$
$CO_2, \text{ fossil} = 1.24 * PVC \text{ plastics}$
$HC \text{ (air)} = 5E-005 * PVC \text{ plastics}$
$HCl \text{ (air)} = 0.0075 * PVC \text{ plastics}$
$NO_x = 7.5E-006 * \text{Heat of combustion}$
$PAH = 5E-009 * PVC \text{ plastics}$
$Particles = 5E-005 * PVC \text{ plastics}$
Emissions to water
$Copper \text{ Cu (aq)} = 0.0005 * Copper, Cu[I]$
Energy
$\text{Heat of combustion} = 17 * PVC \text{ plastics}$
Energy carriers
$\text{Energy steam/heat} = 0.8 * \text{Heat of combustion}$
Materials/Products
$Copper, Cu[I] = Copper, Cu[o]$
Solid wastes
$Slag \text{ and Ash} = 0.34 * PVC \text{ plastics}$

1) Data calculated by IVL ⁷.

Table 54 Parameter specification for the CASICO cable incineration module.

Inputs		Outputs	
Materials/Products		Chemicals	
CASICO plastics	kg	Cl	kg
Copper, Cu	kg	Emissions	
Products		TCDD eqv.	kg
Cable	km	Emissions to air	
		CO	kg
		CO ₂ , fossil	kg
		HC (air)	kg
		NO _x	kg
		PAH	kg
		Particles	kg
		Emissions to water	
		Copper Cu (aq)	kg
		Energy	
		Heat of combustion	MJ
		Energy carriers	
		Energy steam/heat	MJ
		Materials/Products	
		Copper, Cu	kg
		Solid wastes	
		Slag and Ash	kg

Table 55 Equations defining the simulation results of the CASICO cable incineration module ¹⁾.

Equations
Chemicals
Cl=0.000231*CASICO plastics
Emissions
TCDD eqv.=1.004E-010*Cl
Emissions to air
CO=0.00035*CO ₂ , fossil
CO ₂ , fossil=1.74*CASICO plastics
HC (air)=5E-005*CASICO plastics
NO _x =7.5E-006*Heat of combustion
PAH=5E-009*CASICO plastics
Particles=5E-005*CASICO plastics
Emissions to water
Copper Cu (aq)=0.0005*Copper, Cu[I]
Energy
Heat of combustion=24*CASICO plastics
Energy carriers
Energy steam/heat=0.8*Heat of combustion
Materials/Products
Copper, Cu[I]=Copper, Cu[o]
Solid wastes
Slag and Ash=0.409*CASICO plastics

1) Data calculated by IVL ⁷.

A4 1.5 Material recycling

Introduction

Material recycling is an important aspect in almost all product analyses concerning environmental issues. It is, however, important to stress that the term recycling includes not only material recycling but also energy recycling or methane production in a landfill.

The material recycling processes in this study covers recycling of copper and thermoplastics. The processes do not include chemical feed stock recycling. The cables are transported to a disassembly station where the cables are broken down to single materials prior to further processing. The screened materials are then sent to the actual material recycling processes. A common process unit is used for the recycling of thermoplastics but the different plastics are recycled separately.

Disassemble process

Disassembly plants for cables exist in a variety of countries around the world. However, true processes for recycling of both the metal (copper) and plastics are still relatively rare. Due to the economic value of the copper, the copper material is often recycled. Many existing plants, however, are still mostly for development purposes. Data for the disassembly process in this study has been based on actual data for a recycling plant.

Most of the process requirements are linked to electric power consumption. Therefore, only the energy use in form of electric power has been considered for the disassembly process of the cables.

The following data has been used for the electric power use:

Primary granulator: 0.324 MJ/kg cable
 Secondary granulator: 0.162 MJ/kg cable
 Separator: 0.018 MJ/kg cable
 Air fan: 0.162 MJ/kg cable

The total electric power use for the process has thus been estimated to 0.67 MJ/kg cables.

Copper recycling

Data available from copper remelting is very limited from an LCI perspective. The data used are estimations. The module contains the recycling process for copper (remelting). Data are based on a simple model of energy use. The energy use is specified below while the data for the recycling of copper is summarised in Table 56:

Electric power: 15.5 MJ/kg Cu
 Fuel/crude oil: 4.9 MJ/kg Cu
 Diesel/crude oil: 0.85 MJ/kg Cu (heavy machines)

Table 56 Data for the recycling of copper⁹.

Values per 1 kg Copper					
Inputs			Outputs		
Energy carriers			Emissions to air		
Electric power	15.5	MJ	CO	0.000137	kg
Energy resources			CO ₂ , fossil	0.457	kg
Crude oil	5.75	MJ	HC (air)	4.40E-05	kg
Materials/Products			N ₂ O	1.36E-06	kg
Copper, Cu	1	kg	NO _x	0.0014	kg
			Particles	7.36E-05	kg
			SO ₂	0.000279	kg
			Emissions to water		
			COD	1.02E-06	kg
			Oil, unspec. (aq)	3.40E-07	kg
			Phenol (aq)	4.85E-07	kg
			Materials/Products		
			Copper, Cu	1	kg

Thermoplastic recycling

The recycling processes of thermoplastics are under development and only small volumes of the total flow of thermoplastics are presently recycled. Thus, the inventory data reflects a relatively small-scale production with modern energy reuse. This module describes a recycling process of a general thermoplastic material. It has not been possible to make a distinction between different thermoplastics. The different plastics can, however, be treated separately. The materials included are shown in Table 57. This module includes cleaning/pre-treatment, grinding, reforming/extruding and energy reuse from cooling water.

Table 57 Inventory data for the mechanical recycling process of thermoplastics⁹.

Values per 1 kg Total plastics					
Inputs			Outputs		
Energy carriers			Emissions to air		
Electric power	1.33	MJ	CO	7.87E-06	kg
Energy resources			CO ₂ , fossil	0.03	kg
Crude oil	0.135	MJ	NO _x	5.60E-05	kg
Natural gas	0.0697	MJ	Particles	3.37E-06	kg
Materials/Products			SO ₂	1.69E-05	kg
Total plastics	1	kg	Materials/Products		
			Total plastics	1	kg

A4 1.6 Electric power production

Hydro power

In the simplified models for electric power production no emissions from hydro power generation are assumed. This is, of course, not completely true but the traditional emissions such as NO_x, SO₂ etc. are relatively low and related to the side activities of the production or to the construction of the production facilities. These side activities or construction effects are not included in this study for any process. Effects of the biogenic CO₂ balance can also occur due to reduced forest/vegetation area in the river system. These effects are not included.

Nuclear based power production

Emissions or energy effects from nuclear power production are difficult to include in an LCA system. The society effects are of a different nature compared to ordinary combustion power generation and risk assessments are normally excluded in LCA studies. This effect has to be borne in mind when the results are analysed. Only a very simple model for nuclear power generation has been used. The LCI input information is summarised in Table 58.

Table 58 *Data for production of nuclear based electric power. Finnish average from 1995. Data cover emissions, materials and energy needed in the production of uranium fuel using typical Canadian uranium ore ¹⁾.*

Values per 1 MJ electric power					
Inputs			Outputs		
CaO	2.67E-005	kg	CO ₂ , fossil	0.00083	kg
H ₂ SO ₄	4E-005	kg	SO ₂	1.1E-005	kg
NH ₃ , chem.	3.89E-006	kg	Electric power	1	MJ
Electric power	0.0042	MJ	Nuclear waste	9.2E-007	kg
Nuclear	1	MJ	waste, industrial	0.00056	kg

1) Data from KCL-database. Data modified by IVL.

Electric power generation with natural gas

This module covers the production of electric power based on natural gas. A condensation power station has been selected, i.e., no use of heat has been assumed. The combustion process has been optimised for NO_x reduction and low NO_x burner has been assumed. A significant desulphurisation of the natural gas has also been assumed. The overall efficiency for power production has been set to 35 %. The pre-combustion effects from the natural gas production have not been included. Similarly, the production of the boiler is outside the scope of this work. The LCI input data is summarised in Table 59.

Table 59 *Production data for natural gas based electric power production. No heat production has been assumed. The production of the natural gas and the boiler is not included ¹⁾.*

Values per 1 MJ Natural gas					
Inputs			Outputs		
Energy resources			Emissions to air		
Natural gas	1	MJ	CO	5.00E-07	kg
			CO ₂ , fossil	0.051	kg
			NO _x	7.00E-05	kg
			Particles	1.00E-08	kg
			SO ₂	1.00E-06	kg
			Energy carriers		
			Electric power	0.35	MJ

1) Estimated and calculated data for the project by IVL.

Electric power generation with fuel oil

An ordinary condensing fuel oil boiler equipped with electrofilter, SO₂ cleaning (90 % reduction) and SNCR (Selective Non-Catalytic Reduction) with optimised combustion control for NO_x reduction (60 % reduction) has been assumed. The overall efficiency for power production has been set to 35 %. The pre-combustion effects from the fuel oil production have not been covered. Similarly, the production of the boiler has been excluded. The LCI input data is summarised in Table 60.

Table 60 Production data for fuel oil based electric power production. No heat production has been assumed. The production of the fuel oil and the boiler is not included ¹⁾.

Values per 1 MJ Crude oil			
Inputs		Outputs	
Energy resources		Emissions to air	
Crude oil	1 MJ	CO	1.00E-06 kg
		CO ₂ , fossil	0.078 kg
		NO _x	6.00E-05 kg
		Particles	4.00E-06 kg
		SO ₂	5.00E-05 kg
		Energy carriers	
		Electric power	0.35 MJ
		Solid wastes	
		Slag and Ash	1.00E-05 kg

1) Estimated and calculated data for the project by IVL.

Electric power generation with hard coal

For power production from hard coal the use of SNCR (Selective Non-Catalytic Reduction) for NO_x reduction and SO₂ cleaning equipment has been assumed. The overall efficiency of the boiler is assumed to be 35 %. The LCI input data is summarised in Table 61.

Table 61 Production data for coal based electric power production. Condensing power has been assumed. The production of the coal and the boiler is not included¹⁾.

Values per 1 MJ Coal				
Inputs		Outputs		
Energy resources		Emissions to air		
Coal	1 MJ	CO	1.00E-05	kg
		CO ₂ , fossil	0.105	kg
		NO _x	5.00E-05	kg
		Particles	2.00E-05	kg
		SO ₂	5.00E-05	kg
		Energy carriers		
		Electric power	0.35	MJ
		Solid wastes		
		Slag and Ash	0.005	kg

1) Estimated and calculated data for the project by IVL.

Electric power production mix

The variation in emissions and resource use from electric power production can be divided in two different and important parts, i.e.:

- those due to technical differences for a certain production type, and
- those due to different production mix in a geographic area.

The variations for a certain production type, e.g. coal based electric power production, can originate from different levels of technology different plants, different cleaning equipment, different fuel qualities etc. In order to describe this situation for any given country an updated set of measurement data are required for all production plants in that region. It is usually not possible to receive this type of information. Thus, in this project standardised electric power production units have been used. In a geographic area the specifications for the power production also vary due to differences in the production mix of different production types i.e. hydro power, nuclear power, coal power etc. This power mix has a strong influence on the overall specifications of the power production. The power mix can easily be achieved for different countries or certain region. In this project a common electric power mix for the OECD countries has been used. The power production mix is shown in Table 62.

Table 62 *Electric power production mix for the OECD countries used in the models.*

Power production type	OECD ¹⁾ (%)
Hydro power	17
Nuclear power	23.4
Coal power	39
Natural gas power	13.3
Fuel oil power	7.3

1) Average electric power production mix for the OECD countries (year 1997). Solar, wind, geo-thermal and renewable, in total 2 % has not been considered.

The schematic method of producing the mix in the LCA model is shown in Figure 60.

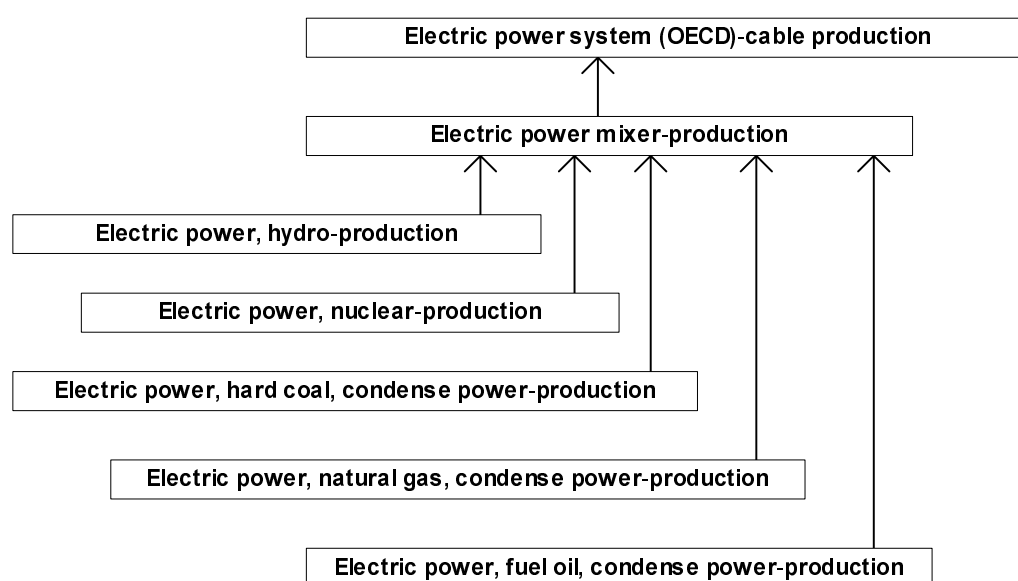


Figure 60 *Schematic illustration of the method used to obtain the electrical power mix for each module requiring power for the LCA model.*

A4 1.7 Transport

Truck

The data covers a heavy diesel truck transport with ~40 tons of load. A truck model of mid-1990s has been assumed. The truck uses city diesel with low sulphur content. The data includes pre-combustion of the city diesel. The LCI input data is summarised in Table 63.

Table 63 LCI data for a general heavy truck transport. Pre-combustion of the city diesel is included¹⁾.

Values per 1 km*ton				
Inputs		Outputs		
Energy resources		Emissions to air		
Crude oil	0.4 MJ	CO ₂ , fossil	0.0294	kg
		HC (air)	5.00E-05	kg
		N ₂ O	5.28E-07	kg
		NO _x	0.00029	kg
		Particles	1.20E-05	kg
		SO ₂	7.42E-06	kg

1) Estimated data by IVL.

A4 1.8 References

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